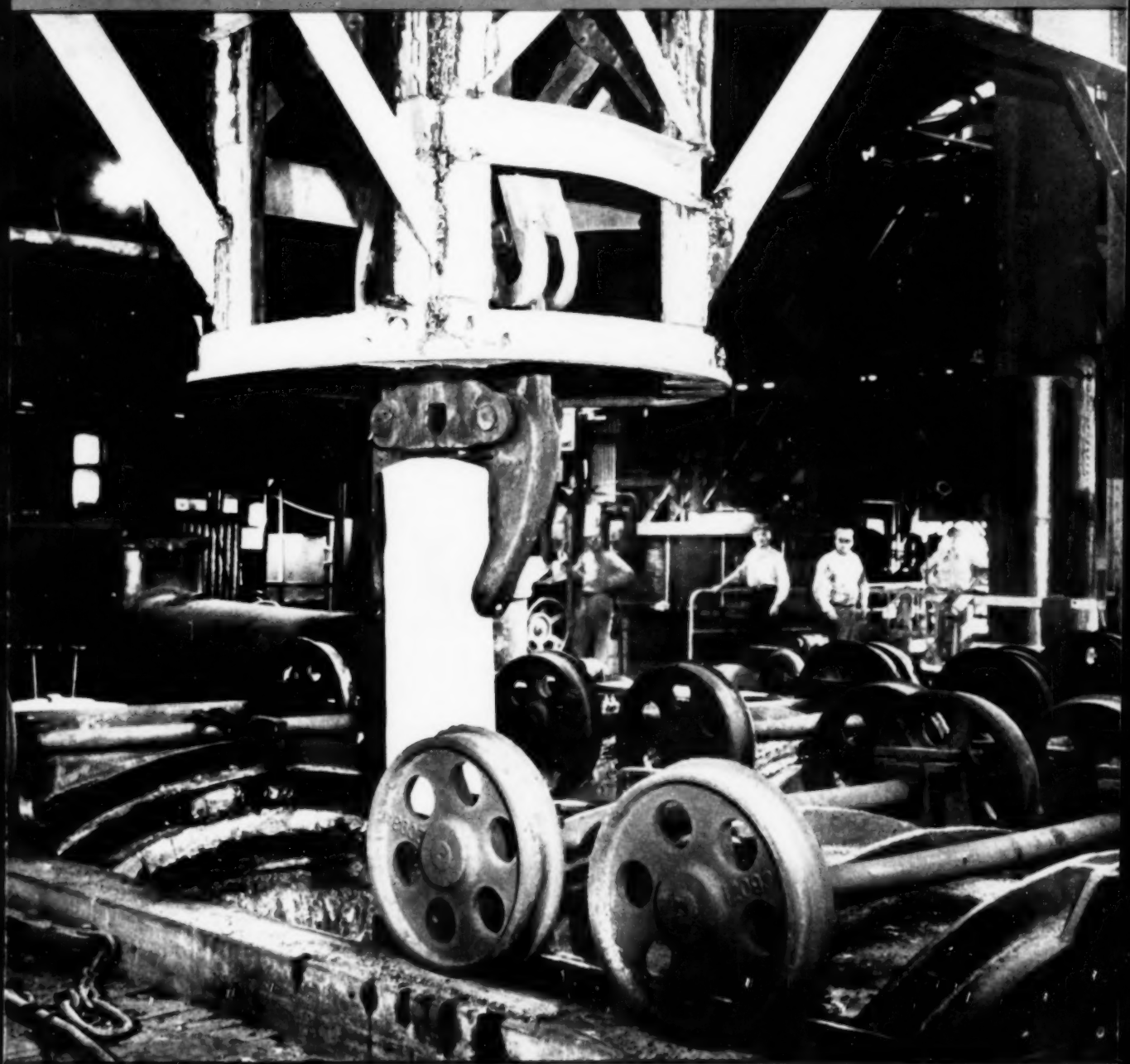
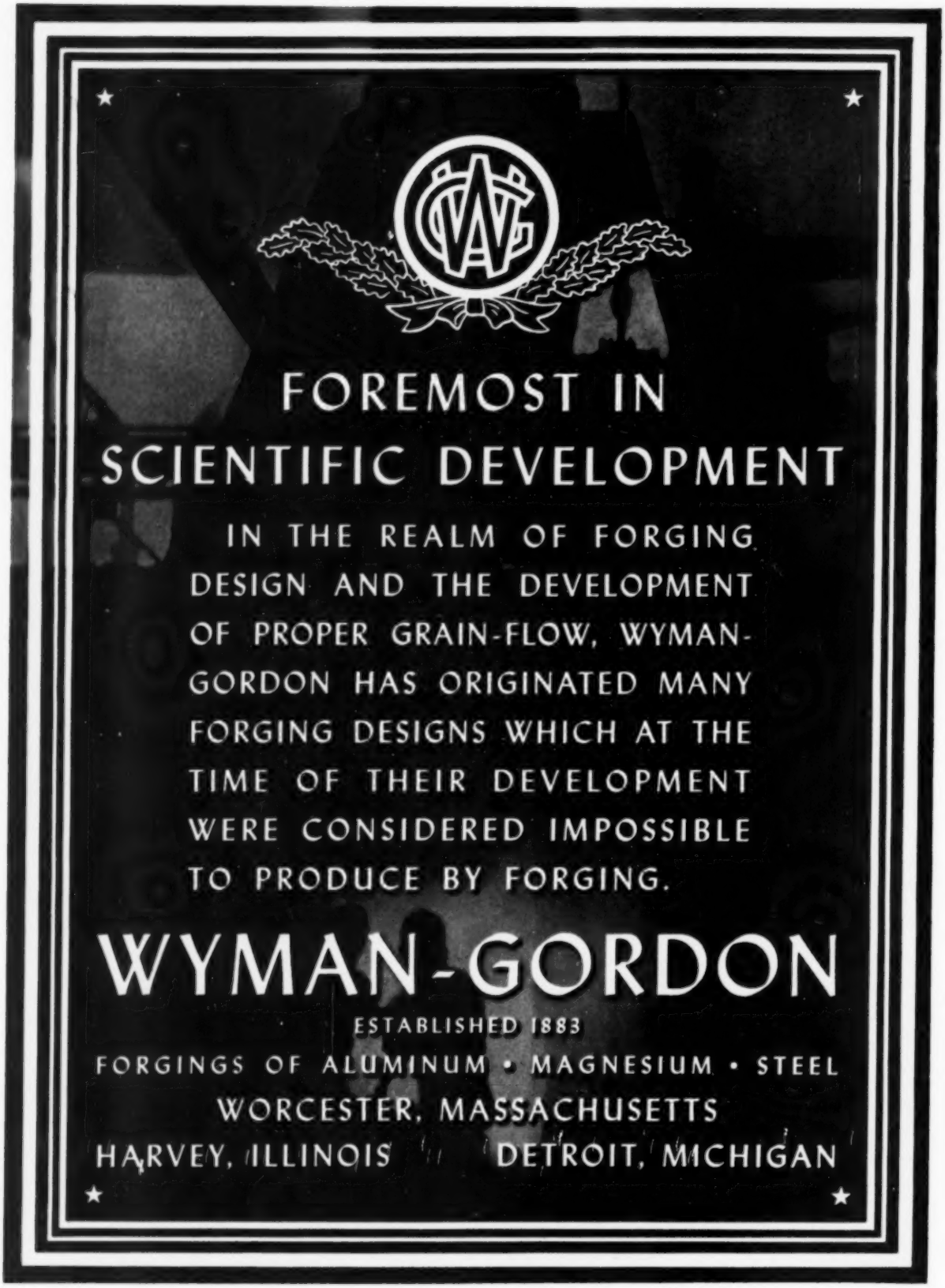
MARCH, 1953

Journal of METALS



March JOURNAL OF METALS Highlights:

"Aluminum Industry Expands for War and Peace" - p. 388
"Silicon Content of Blast Furnace Iron Lowered by Oxygen Injection in Ladle" - p. 396
"Residual Stresses Introduced During Metal Fabrication" - p. 405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VOL. 5, NO. 3 MARCH, 1953

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COVER

A titanium alloy slab, weighing 1500 lb, is removed from soaking pit for rolling in a continuous mill at the Brackenridge, Pa., plant of Allegheny Ludlum Steel Corp., for Titanium Metals Corp. of America.

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Books for Engineers

Structural Adhesives. *Lange, Maxwell, and Springer, Inc.* $4.20, 203 pp., 1952.—The book is composed of a series of lectures on the technology of synthetic resin given in Cambridge at the summer school held by Aero Research Ltd., Duxford, Sept. 23 to 29, 1951. The study is of practical value to engineers engaged in the aircraft and electrical industries. Specific applications are studied in two sections: 1—Adhesives in the woodworking industries, covering gluing, glued joints, radio frequency heating, etc.; 2—adhesives in the engineering, electrical manufacturing and allied industries, covering metal bonding, bonding of ceramics, etc. Introductory lecture covers the chemical fundamentals of various adhesive materials, the strength of glued joints, and other basic ideas.

Metallurgie, by R. Cazaud. *Dunod, Paris.* 450 F, 372 pp., 1953.—This is a condensed metallurgical pocketbook covering some 30 metals, chiefly those of commercial importance. Properties, basic qualities, and metallurgical characteristics are given briefly. Separate sections are devoted to corrosion, heat treatment methods, and test methods for metals. Table data and some common formulas are included in the back of the book.

Korrosionstabellen Metallischer Werkstoffe, third edition, Franz Ritter. *Springer-Verlag,* Vienna. $8.20, 283 pp., 1952.—Tables of the corrosion of metals arranged by the German name of the attacking substance. The corrosive effects are expressed in grams per square meter per day and millimeters per year. In addition to the main section of tables, the book includes an introduction to the use of the tables, a numerical index to the more than 900 metallic materials considered, an extensive list of original literature sources, and a supplement containing information not given in the main tables. Considerable new information has been added to this edition.

Identification and Qualitative Chemical Analysis of Minerals, second edition by Orsino C. Smith. *D. Van Nostrand Co., Inc.* $7.50, 385 pp., 1953.—All of the more than 2000 known minerals are classified in the mineral identification tables, first in groups by specific gravity and, within each group, by hardness. Other distinguishing characteristics, including distinctive chemical reactions, are arranged for easy reference. A complete scheme of qualitative analysis is presented, followed by blowpipe reactions and bead tests with colored plates for direct comparison with analytical results. A large number of other plates show the minerals in natural colors and the appearance of those that fluoresce under ultraviolet.

Electromagnetics, by John D. Kraus. *McGraw-Hill Book Co.* $9.00, 604 pp., 1953.—The book is an extensive treatment of basic principles of electromagnetic-field theory and their application to electronics, power, radiation, and propagation. The first half of the book serves as an introductory field-theory course and covers static electric and magnetic fields, steady currents, and changing electric and magnetic fields. The second half, a continuation on a more advanced level, treats plane waves in dielectric and conducting media, transmission lines, wave guides, antennas, and boundary-value problems. A table of units and various basic mathematical relations are included in an appendix.

Electrochemical Data, by B. E. Conway. *Elsevier Publishing Co.* $8.75, 374 pp., 1952.—The author provides detailed tabular information on aspects of electrochemistry for which exact data of known accuracy are available. In addition to information on pure electrochemistry—electrode potentials, solvation and ionic interaction in aqueous and nonaqueous solutions—data have been included on quantitative aspects of applied electrochemistry—on slags and fused melts and on applications in the field of biophysics. Explanatory introductions to chapters are included, and extensive references to original information sources are given.

Automation, The Advent of the Automatic Factory, by John Diebold. *D. Van Nostrand Co.* $3.00, 181 pp., 1952.—The author makes no attempt to make a contribution to technological knowledge, but rather intends to present an essay on the business problems of automation and use of technological developments to the business man. Automation denotes not only automatically controlled operation, but also such aspects as product and process redesign for automatic operation, the theory of communication and control, and the design of specialized machinery. The whole thing is viewed as a distinct area of industrial endeavor. The book points out the obstacles and limitations along with the possibilities of automation; suggests solutions for problems which arise; describes existing samples of partial achievement; evaluates computers and their application to production scheduling, unit operations analysis and similar control procedures; and discusses the important economic and social effects of the new technology.

Western Resources Handbook. *Stanford Research Institute.* One primary subscription, $250, secondary subscription, $100. The handbook is a compilation of economic and technical data on the resources of the 11 western states. It is not confined to natural resources, but includes also

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The authors of the book **Advanced Mechanics of Materials,** published by John Wiley & Sons, Inc. (JOURNAL OF METALS, January 1953), are Seely and Smith.

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the agricultural, manpower, industrial and other resources necessary to the western economy. Presentation is graphic, the Handbook being made up primarily of tables, charts, and maps, with a minimum of text. Looseleaf makeup allows periodic additions. All Government and private data available to the Institute are used in the preparation of the Handbook. The Institute plans to remedy certain gaps by developing data which has not existed in organized form. The Handbook will be built up, rather than published complete at one time. The necessary binder, indexing tabs, introductory material, and other necessities are included in the subscription.

The Engineer's Approach to the Economics of Production, by John Reid Dick. *Sir Isaac Pitman & Sons, Ltd.* 21s, 248 pp., 1952.—The book deals with the engineer's problems relating to capital investment and operating costs. It covers behavior of factors determining efficient production. The application of theories of economics is used to further the ideal situation of optimum efficiency with minimum costs.

Inorganic Chromatography, by Orsino C. Smith, *D. Van Nostrand Co., Inc.*, $5.00, 134 pp., 1953.—Wide usefulness of chromatographic methods in inorganic separations and determinations is fully explained. Basic research is thoroughly covered, including the factors influencing absorption, column chromatography, paper chromatography, chromatography by ion exchange, and other fundamental topics. It then describes in detail a systematic plan of inorganic analysis by chromatographic methods, including rare metals as well as common ones.

Steel Castings Handbook. *Steel Founders' Society of America.* $4.00, 520 pp., 1953.—The revised edition, first published in 1950, has been reprinted. It contains 440 illustrations, and 120 tables. Sixteen chapters cover steel casting activities from the angle of history, and data valuable to engineers, designers, production executives, students, and others active in the field.

Transactions of the Danish Academy of Technical Sciences, $3.00, 144 pp., 1952.—The volume contains a single paper, *Some Experiments with Sleeve Bearing Metals,* by Borge Lunn. Existing practical experience is compared with results obtained from a new test method. Based on these results and the latest recognition from other research work in the same area, a hypothesis has been set up for the function of sleeve bearings.

Gasification and Liquefaction of Coal. *American Institute of Mining and Metallurgical Engineers.* $6.00 to nonmembers, $4.20 to members, 221 pp., 1953.—The volume contains the papers presented at the Symposium on the *Gasification and Liquefaction of Coal,* held at the Annual Meeting of the AIME, February 1952. It presents a comprehensive view of worldwide developments in many phases of coal gasification. New and current developments dealing with techniques, plant design, direct hydrogenation, chemicals output, underground gasification, and gas economics are reviewed.

MacRae's Blue Book, 60th edition. *MacRae's Blue Book Co.* $15.00, 1953. —In this latest edition, classifications have been brought up to date and new listings added. Included is a separate bound edition of the alphabetical address section for dual use of engineering or sales dept. The main volume contains manufacturer's addresses, list of manufacturers by classification, and trade mark information.

American Electricians Handbook, 7th edition, revised by Clifford C. Carr. *McGraw-Hill Book Co.* $10.00, 1953. —The latest edition of this reference book is now in accord with the 1951 National Electric Code. It offers tables and information on selection installation, maintenance and operation of electrical equipment. Fundamentals of electricity are covered without use of advance mathematics. The *Handbook* also includes time saving methods in calculating electric circuits and in planning power and lighting installations. Electron tubes, circuits, electronic devices in industry, control generators and electronic control of motors are also discussed.

Foundation Engineering, by Ralph B. Peck, Walter E. Hanson, and Thomas H. Thornburn. *John Wiley & Sons, Inc.* $6.75, 410 pp., 1953.—The book contains the basic information required for the selection, design, and construction of substructures. Types of foundations met in everyday practice are emphasized. Material is provided for use in investigating and evaluating subsurface conditions, selecting the most suitable types of foundations for a given site, judging the performance of each type in service, and designing the structural elements of each type.

Screw Thread Manual. *American Society of Mechanical Engineers.* $2.50, 68 pp., 1953.—The book intends to supply shopmen, tool designers, and draftsmen with information needed when selecting, designing, testing, or making the most used screw threads. It contains the limits of size of threads constituting the bulk of use, standard coarse, fine, and 8-pitch thread series of classes 2A and 2B from the smallest to those of 1½ in. normal diam. Using simple arithmetic, the book shows how to calculate all other standard threads of the American Unified threads and special threads of the new A and B classes.

Manual of Cutting Metals, second edition. *American Society of Mechanical Engineers.* $10.00, 1953.—Written in collaboration with 22 specialists, this edition of the manual enlarges upon the first and incorporates a more descriptive presentation of tool materials and their treatment; of work materials and the relations of their behavior and properties to microscopic structure; and much new material on the types, purposes and applications of cutting fluids. New tables are also included in the volume, covering unit-horsepower and machinability ratings for a great number of steels of various hardnesses for specific tools and cuts, and other topics.

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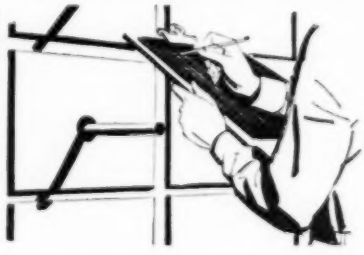

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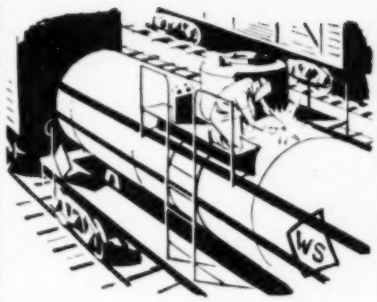

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MEET THE AUTHORS

Kent R. Van Horn (p. 405), director of the Alcoa aluminum research laboratories is the Institute of Metals Div. Lecturer for 1953. A native of Cleveland, Dr. Van Horn is a graduate of Case Institute of Technology (B.S., M.S., Ph.D.). He received his Ph.D. in 1929 and then joined the Aluminum Co. of America as a research metallurgist. From 1945 to 1948 he was chief of the Cleveland research div. In 1948 Dr. Van Horn was appointed assistant director of the aluminum research laboratories. Two years later he was named associate director and in 1952 was appointed director. A member of AIME, he also holds membership in the British Institute of Metals, ASTM, ASM, and Non-Destructive Testing Society. He has authored various papers and presented a dozen or so before AIME.

Fred J. Meek (p. 404) was born in Chicago and attended the University of Illinois. He was employed in various mining positions for several years. After his discharge from the Army, Mr. Meek joined the Ripon Electric Co. as manager. In 1928 he was associated with the Lawsonia Realty Corp., Home Builders, and Country Club. From 1931 to 1932 he had been with the Barton Corp. and then joined the Eagle Picher Lead Co., Hillsboro, Ill. as plant engineer in charge of the engineering dept. Later Mr. Meek joined the American Zinc Co. of Illinois and he is now located at East St. Louis, as plant engineer.

K. R. VAN HORN

F. J. MEEK

C. R. Taylor (p. 401), AIME Member born at Billings, Mont., is now a resident of Trenton, Ohio. Dr. Taylor is a graduate of Oberlin, Ohio State University, and University of Cincinnati. In 1933 he joined the Armco Steel Corp. as a laboratory assistant in the metallurgy dept. He was made research assistant in 1936, junior research engineer a year later, became research engineer in 1941, was named senior research engineer in 1942, and has been supervising metallurgist since 1944. This AIME Member enjoys flying, photography, orinthology, and astronomy as his avocations. Dr. Taylor has presented several papers before AIME.

Lloyd H. Banning (p. 423), chief of the ferrous metals branch at the Albany, Ore. station of the Bureau of Mines, was born at St. Lawrence, S.D. He is a graduate (B.S., 1931), from the South Dakota School of Mines. His professional experience includes the manufacture of titanium dioxide at the chemical and pigment div., Glidden Co., Baltimore. He has also been engaged in mining and concentration of manganese ores and assaying and mill operation at gold cyanidation plants. The greater part of the last ten years he has been a metallurgist for the U. S. Bureau of Mines. Mr. Banning's hobby is raising cattle on his farm near Albany, Ore.

C. R. TAYLOR

L. H. BANNING

F. R. Morral (p. 431) is a graduate of Massachusetts Institute of Technology (B.S. in 1932) and Purdue University (Ph.D. in 1940). Dr. Morral was in Sweden and Spain for several years prior to joining the Continental Steel Corp. as research metallurgist in 1939. He joined the staff of Pennsylvania State College in 1941 and was assistant professor of metallurgy. He was associated with the Mellon Institute and in 1944 became connected with the American Cyanamid Co. as group leader in the metals trades laboratory. Prior to joining Kaiser Aluminum & Chemical Corp. as head of the X-ray diffraction dept., he was associate professor of materials engineering at Syracuse University. Dr. Morral is a member of the AIME, Columbia Section; Iron and Steel Institute, England; Institute for Metals, England; American Crystallographic Society; ASM; Wire Assn.; American Society of Engineering Education; and Instituto del Hierro y del Acero (Madrid).

Frederick F. Frick (p. 395) is a graduate of the Colorado School of Mines. Mr. Frick was born in Chicago and is presently located at Anaconda, Mont. as a research engineer for the Anaconda Copper Mining Co. As a member of the AIME, Mr. Frick has previously presented a paper on sponge iron.

R. H. Wynne (p. 436) had been employed by the Westinghouse Electric Corp. from 1909 until 1950, when he retired. Born in Norfolk, Va., Mr. Wynne attended Bethany College (A.B.) and University of Michigan (B.S.). In 1951 he was recalled by Westinghouse to conduct research on surface treatment of germanium for use in transistors. Gardening, fishing, and nature study, especially botany, occupy Mr. Wynne in his spare time.

K. T. Aust (p. 431) was born in Toronto and received his B.A.Sc., M.A.Sc., and Ph.D. degrees from the University of Toronto. In 1946 Dr. Aust was physical metallurgist for the U. S. Metals Refining Co., Carteret, N. J. He has been with Kaiser Aluminum & Chemical Corp., Spokane, since 1950. *Solubility of Titanium in Liquid Magnesium* is one of the papers Dr. Aust has presented previously.

Pierre J. Leroy (p. 396) is assistant to the chief of the steelmaking dept., Institut de Recherches de la Siderurgie, St. Germain, France. Born in Paris, Mr. Leroy received his degree in metallurgy from the Ecole Superieure des Mines de Nancy in 1943. Prior to joining the I.R.Sid., he had been with the Societe Metallurique de Senelle-Maubeuge engaged in work on Bessemer converters and open hearth furnaces. Mr. Leroy is quite interested in Bessemer operation to the extent that his hobby is the control of the basic Bessemer operation. The lighter side of his hobbies is the discovery of the U.S.A. Mr. Leroy has presented several technical papers.

R. L. Fullman (p. 447) has been associated with the General Electric Co. research laboratory since 1948. He is presently a research associate. Born in Sewickley, Pa., he received his B.E. from Yale in 1943 and his D.E. in 1950, also from Yale. Now a resident of Schenectady he is a Junior Member of the AIME New England Local Section. As his hobbies, Dr. Fullman enjoys photography, woodworking, and music.

P. J. LEROY

R. L. FULLMAN

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Recent Graduate, M.S. in metallurgy, with emphasis on magnetics; B.S. in physics; industrial experience helpful but not essential, or B.S. in metallurgy and 2 years experience in a magnetic measurements laboratory. Location, midwest. Y8080(b).

Kiln Superintendent to take charge of the calcining and nodulizing section of a manganese plant designed to produce 500 tons per day of metallurgical grade nodules. Will take charge of a crew of about 25 men. Location, Nevada. Y8069.

Sales Engineer, metallurgical or mineral dressing training and experience, to sell ore dressing equipment. Reasonable traveling. Salary, $5200 to $6500 a year. Territory, eastern seaboard. Y8045.

Metallurgist, graduate, with considerable flotation plant experience. The operation entails a problem in handling lead-copper ore, and experience along these lines extremely beneficial. Location, midwest. Y8036.

Gray Iron Foundry Superintendent or Manager, 30 to 45, to supervise overall operations. Must have had five years experience in foundry operation as foreman or superintendent on hand and machine work. Salary, about $8000 per year. Company will negotiate placement fee. Location, down state Illinois. T-9516.

Ceramists and Metallurgists for research department (c) and **Ceramists and Metallurgists** for manufacturing departments (d). Location, upstate New York. Y8058.

Assayer to take charge of large laboratory. Should have had five to ten years experience in the assaying of precious metals. Salary open. Location, northern New Jersey. Y7929S.

MEN AVAILABLE

Metallurgist, French, 39. Fifteen years experience large American, French, and German organizations; mainly in research. Broad knowledge ferrous and nonferrous from conventional to vacuum metallurgy. Can organize research projects of fundamental nature. Location immaterial. M-102.

METALLURGIST

Graduate within past 5 years, with B.S. or M.S. degree. Preferably some experience as mill metallurgist in plant producing flat rolled steel. Excellent opportunity as metallurgical sales engineer for company producing titanium mill products.

Box C-12

JOURNAL OF METALS

RESEARCH METALLURGIST. Experienced in ferrous mechanical and physical metallurgical research, either industrial or academic. Graduate degree preferred. Research department of a major user of metal products located in the Chicago area. Age under 40. All replies will be held confidential.

Box C-10 JOURNAL OF METALS

ACADEMIC OPENING

Metallurgist, having doctorate, for teaching and research with emphasis in physical metallurgy. Promising opportunity to grow with an expanding graduate program. Salary and rank commensurate with qualifications. Write to C. S. Crouse, Department of Mining and Metallurgical Engineering, University of Kentucky, Lexington, Kentucky, stating your qualifications and salary required.

METALLURGIST—Bachelor's or Master's degree for research and development work on ferrous metals and alloys. Work comprises a great variety of metallurgical problems in the high temperature field as well as problems connected with processes in chemical, oil, and pulp and paper industries. Association with a large staff of engineers and physical scientists offers an unusual opportunity for professional development. Advancement commensurate with achievements. Large research center of internationally known industrial firm completely equipped with all required modern facilities. Inquiries will get immediate confidential consideration.

Box C-11 JOURNAL OF METALS

METALLURGICAL RESEARCH

The Armour Research Foundation of the Illinois Institute of Technology solicits employment inquiries from metallurgists interested in physical metallurgy, welding, powder metallurgy, foundry, and others. The requirements for current research and development openings cover a wide range of professional stature—from recent grads to mature research scientists. The Armour organization affords an unusual opportunity for continued professional development through pleasant associations with other metallurgists having mutual technical interests. Your inquiry will be confidential, and we will be pleased to respond with further information about current opportunities.

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Metallurgist experienced in foil production methods from ingot casting and rolling operations to finishing required by prominent aluminum producer. Excellent opportunity for thoroughly trained and experienced nonferrous man. Give complete information on age, education, experience, and salary required.

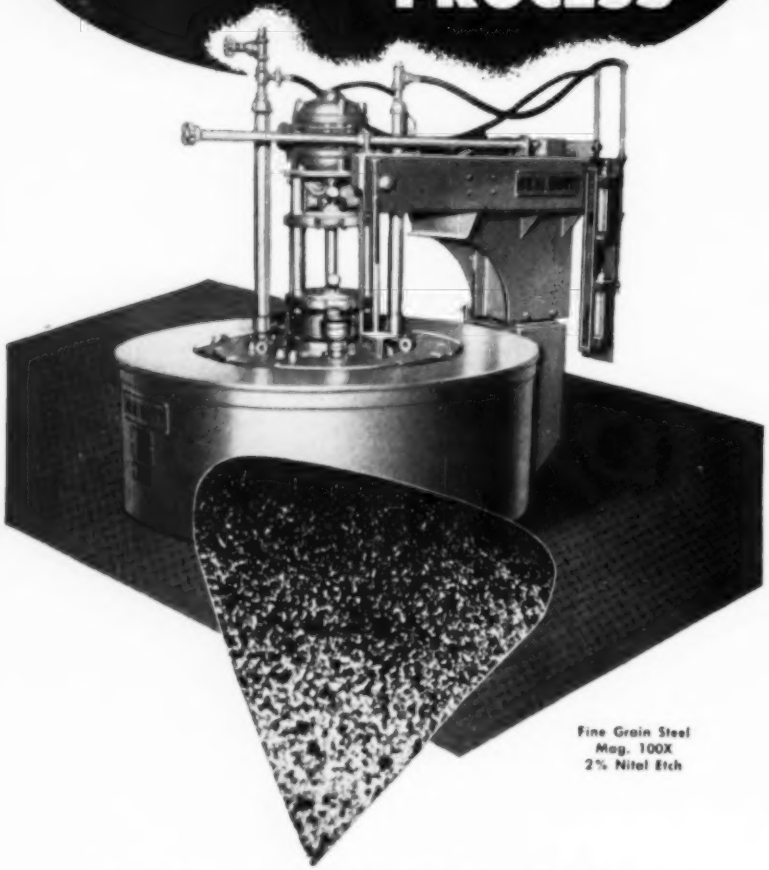
Box B-5 JOURNAL OF METALS

WANTED

Metallurgist with experience or training in nonferrous metallurgy. Powder metallurgy experience desirable but not essential. Work on research and development of special products in small community in northwestern Pennsylvania.

Box A-3 JOURNAL OF METALS

CARBON CONTROL in the CARBURIZING PROCESS



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Industrial Notes . .

• Installation of a rotary hearth bloom heating furnace in the tubular products div. steel mill of Babcox & Wilcox Tube Co. at Beaver Falls has been completed by George J. Hagen Co., Pittsburgh. The furnace is equipped with automatic charging and unloading equipment, automatic furnace pressure control, automatic combustion control and automatic temperature control, providing a completely automatic installation from bloom storage table to the mill.

• **A contract for the design and construction of two 15-ft diam butterfly valves for use in aircraft propulsion research has been awarded to Salem-Brosius, Inc., by the National Advisory Committee for Aeronautics, Lewis Flight Propulsion Laboratory, Cleveland. The valves are said to be the largest of their kind ever required.**

• The annual Doehler-Jarvis Award will again be presented by the American Die Casting Institute for outstanding contribution to the advancement of the die casting industry or to the art of die casting. The award committee will select the winner on the basis of technical achievement, advancement in plant operation, or other activities not primarily of a scientific or operational nature that result in the enhancement of the reputation of die casting. The Award consists of a plaque and cash honorium of not less than $500. Nominations will be received until Apr. 30, 1953.

• *Whitehead Metal Products Co., Inc., has been appointed distributor of Vancoram products to iron foundries in northeastern U. S., by Vanadium Corp. of America. Whitehead has offices and warehouses in New York City; Buffalo; Syracuse; Philadelphia; Baltimore; Harrison, N. J.; and Cambridge, Mass. They also operate offices in New Haven; Albany; Schenectady; Rochester; and Richmond, Va.*

• Germanium is being sought in flue dust and coal ash by the U. S. Bureau of Mines. The project is jointly conducted by the Mines Bureau and U. S. Signal Corps Engineering Laboratories, Fort Monmouth, N. J. JOURNAL OF METALS, November 1952 carried an article which in part discussed British pilot plant operations along the same lines. Bureau chemists are presently working on a method for measuring percentage of germanium in coal ash and flue dust. Germanium content in coal itself is about one-thousandth of 1 pct,

according to the Bureau. Samples of flue dust and coal ash are being taken from public utility plants in Pennsylvania, Ohio, Kentucky, Illinois, Alabama, and West Virginia. The Tennessee Valley Authority may also provide samples.

• *An aluminum rolling mill producing sheet strip and circular shapes is to be constructed somewhere on the west coast by the Harvey Machine Co. Leo M. Harvey, president of the firm, said the plant will cost about $20 million. It will have a capacity of 60 million lb of aluminum products annually. Plant site was not disclosed.*

• Awards to be presented for papers on resistance welding by the Resistance Welder Mfrs. Assn. total $2250. Papers may come from three sources, industrial, university staff, or university undergraduate. The contest is open to anyone from the U. S. or its possessions, and Canada. It is also open to any member of the American Welding Society anywhere in the world. Information can be obtained from Resistance Welder Mfrs. Assn., 1900 Arch St., Philadelphia, Pa.

• **A new coke battery of 61 ovens has gone into operation at U. S. Steel Co.'s Clairton works under a long range plan started by the company in 1946 to rebuild existing coke oven facilities at the installation. One more battery is scheduled to start up in May.**

• Technical assistance for large scale production of titanium oxide in Japan will be given by the Glidden Co. under terms of an agreement signed by the American company. Plans call for construction of a $6 million titanium dioxide plant in Japan by the Ishihara Chemical Co. According to Dwight P. Joyce, Glidden president, Ishihara has excellent sources of ilmenite in Malaya and is a producer of sulphuric acid, both necessary for production of titanium oxide.

• *Export Import Bank has authorized a credit in favor of Nacional Financeria, S. A., of Mexico for expansion of the Hoja Lata Ye Lamina steel mill at Monterrey, Mexico. New facilities planned are an electric melting furnace, hot strip mill, continuous pickler, cold strip mill, strip cleaning line, annealing furnace, tempering mill, and shearing and coil slitting lines. Improvements are expected to increase annual capacity from 30,000 tons to about 50,000 tons of plate, coil, and sheet. Hoja Lata Ye Lamina was incorporated in 1952.*

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SOLID STATE PHYSICISTS — Ph.D. or equivalent in experience in physics with a specialty in solid states work preferred. Will study electrical and optical behavior of semi-conducting materials.

METALLURGISTS — advanced degree or experience required. Will work on metallurgical preparations of semi-conducting devices.

ELECTRONIC — with graduate work or experience in product or circuit design and development.

Send complete resume to:

Mr. Robert L. Keller

SYLVANIA ELECTRIC

Electronics Division

WOBURN, MASS.

— Coming Events —

Mar. 3-11, American Institute of Chemical Engineers, Buena Vista Hotel, Biloxi, Miss.

Mar. 4, AIME, Chicago Section, Chicago Bar Assn., Chicago.

Mar. 7, Symposium on Air Pollution, Wagner College, Staten Island, N. Y.

Mar. 11, AIME, Connecticut Section, Waterbury, Conn.

Mar. 11, AIME, Chicago Open Hearth Local Section, all day meeting, Del Prado Hotel, Chicago.

Mar. 13, AIME, St. Louis Local Section, Hotel York, St. Louis, Mo.

Mar. 16-20, National Assn. of Corrosion Engineers, annual conference and exhibition, Hotel Sherman, Chicago.

Mar. 18, AIME, National Open Hearth Steel Committee, Roger Young YMCA, Los Angeles.

Mar. 18-20, ASTE, annual meeting, Statler Hotel, Detroit.

Mar. 23-27, ASM, western metal congress and exposition, Pan-Pacific Auditorium, Los Angeles.

April-May, Empire Mining and Metallurgical Congress, Australia and New Zealand.

Apr. 1, AIME, Chicago Section, Chicago Bar Assn., Chicago.

Apr. 12-16, Electrochemical Society, Inc., spring meeting, Statler Hotel, New York.

Apr. 12-May 23, Empire Mining and Metallurgical Congress, Australia-New Zealand.

Apr. 18, AIME, Student Conclave and St. Louis Local Section, Missouri School of Mines.

Apr. 20-22, AIME, National Open Hearth and Blast Furnace, Coke Oven and Raw Materials Conference, Hotel Statler, Buffalo.

Apr. 21, Assn. of Consulting Chemists & Chemical Engineers, Inc., symposium and dinner, Hotel Belmont Plaza, New York.

Apr. 23-25, AIME, New England Regional Conference, General Electric Laboratory, Schenectady, N. Y.

Apr. 25-May 10, Liege International Fair, Liege, Belgium.

Apr. 26-29, American Institute of Chemical Engineers and **Chemical Institute of Canada,** Royal York Hotel, Toronto.

May 14-16, AIME, Pacific Northwest Metals and Mineral Conference, joint meeting, Metals Branch and Industrial Minerals Div., Ben Franklin Hotel, Seattle.

May 14-23, International Petroleum Exposition, Tulsa.

May 18-22, National Materials Handling Exposition, Convention Hall, Philadelphia.

May 20, AIME, National Open Hearth Steel Committee, Western Section, field trip.

June 3-7, Chemical Institute of Canada, Windsor, Ont.

June 15-19, Basic Materials for Industry, conference, Hotel Roosevelt; exhibition, Grand Central Palace, New York.

Sept. 21-23, American Mining Congress, Metal and Nonmetallic Mineral Mining Convention, Olympic Hotel, Seattle.

Oct. 7-9, National Assn. of Consulting Engineers, south central region, Mayo Hotel, Tulsa, Okla.

Oct. 19-21, AIME, Institute of Metals Div., fall meeting, Hotel Allerton, Cleveland.

Oct. 19-23, National Metal Congress and Exhibition, Cleveland.

Oct. 27, Assn. of Consulting Chemists & Chemical Engineers, 25th anniversary annual meeting, Hotel Belmont Plaza, New York.

Oct. 28-31, AIME, El Paso Fall meeting, El Paso.

Oct. 29-31, National Council of State Board of Engineering Examiners, Annual Meeting, Plaza Hotel, San Antonio, Texas.

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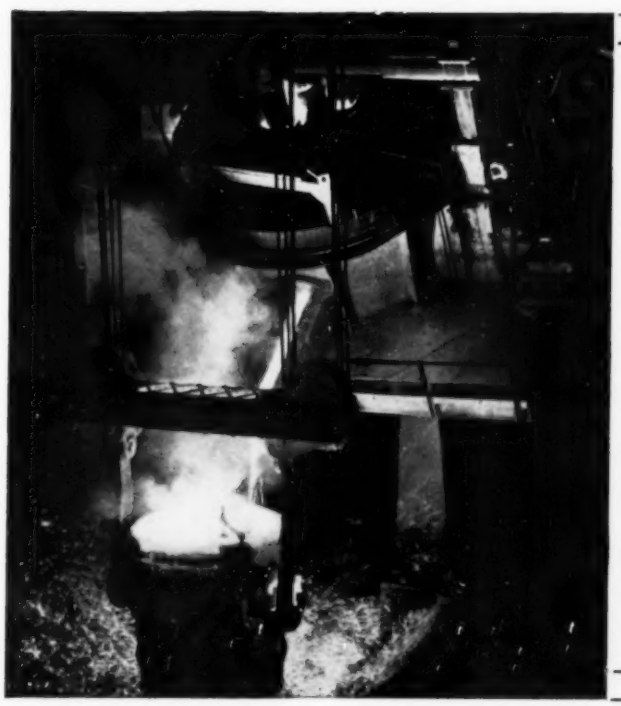

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TWO thirds of the $3.5 billion spent for research in the U. S. during the past year came from private companies. The Government spent another fourth, while the remainder came from colleges and universities. The Dept. of Labor, in its survey, *Industrial Research and Development,* received information from some 2000 companies, employing nearly 94,000 research engineers and scientists as of January 1952. Research staffs, including both professional and supporting personnel, totaled 234,000. Average ratio of supporting personnel to research engineers and scientists was about 5 to 1. Average cost per research engineer or scientist was $22,100 in 1951. All research employees, including supporting personnel as well as engineers and scientists, cost an average of $8900. One of the important items reported was that one fourth of all research engineers and scientists included in the study were in classifications most liable for military service. An item of concern is the rapid turnover of research personnel. The average number of research people leaving reporting companies during 1951 was 16.4 per 100 employed at the end of the year. Hardest hit was the aircraft industry, where competition for engineer personnel since outbreak of Korean hostilities has been most severe.

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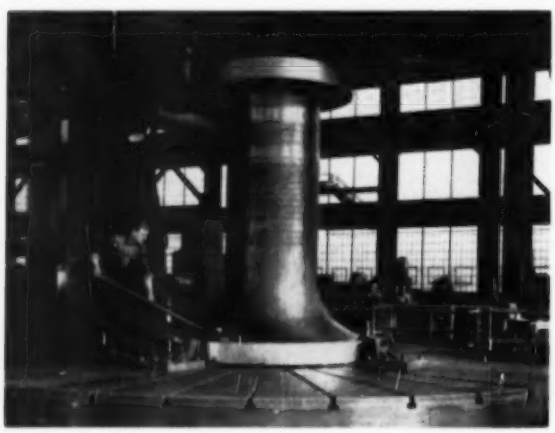
INDUSTRY will continue to be hampered by a shortage of engineers during 1953, according to Engineering Manpower Commission of Engineers Joint Council The commission asserted that 40,000 new engineering graduates are needed by U. S. industry, but only 23,000 will graduate this year, 19,000 in 1954, 22,000 in 1955, and 29,000 in 1956. The Commission reports, however, that companies have learned to use the engineer's talents more efficiently. Engineers have been relieved of work that can be done by nonprofessionals or technicians.



A 38-ton intermediate shaft for the giant hydroelectric plant at McNary Dam is removed from vertical boring machine at the Bethlehem, Pa., plant of Bethlehem Steel Co. Fourteen generators with a total capacity of nearly a million kw will be operated at the $280 million dam on the Columbia River.

WHILE U. S. mineral production continued at a rate which would have been considered phenomenal prior to World War II, output during 1952 decreased slightly in physical volume compared with the previous year. Dollar value, $13,500,000,000, was about equal to 1951. Slightly increased prices kept the figures roughly the same. However, while coal production declined, production was balanced by increases in most other minerals.

Strikes reduced the supply of iron ore but the enlarged Great Lakes fleet and an almost maximum effort on the part of producers averted a shortage among consumers this winter. Ferroalloy metals, with the exception of nickel, showed a marked increase during the year. International allocation plans for cobalt and tungsten were dropped by the end of 1952. Sharp increases in manganese imports, coupled with the drop in consumption by the steel industry because of the strike, made possible replenishment of stockpiles. Tungsten supplies also improved because of the same conditions. Chromite production in the U. S. increased about 35 pct, while imports gained 13 pct. Nickel continues to be scarce in comparison to industry needs, despite stepped-up Canadian production and resumption of Cuban activity.

Copper, despite a continued heavy domestic demand, showed no increase in production. Heavy imports at the end of the year resulted in a greater supply of foreign copper, but the amount available was no where near what U. S. industry required. Copper producers are looking to the administration for relief from what they consider an unfair situation. A copper price ceiling of 24½¢ has been in effect since beginning of the Korean War. The international market price of copper rose to 35¢ per lb and at times more than that. About 40 pct of copper used in the U. S. comes from abroad. Copper fabricators must, under Government regulations, obtain only 60 pct of base requirements from domestic sources, with remaining needs coming from foreign sources. At the same time, fabricators can only pass on 80 pct of the additional cost of the foreign product to consumers.

With the new administration overtly favoring decontrol wherever and whenever possible, copper producers and fabricators are looking to the Government for a quick change in the situation. If decontrol does come, two immediate effects are expected. The first would be an increase in copper supply arising from release of copper scrap withheld from the market in expectation of higher prices. The second result looked for is an increase in domestic copper price, with some experts predicting a rise as high as 35¢. Copper supplies may be slightly better in 1953, according to the report of the Director of Defense Mobilization, but major increases of supply from large expansion projects will not arrive upon the scene until sometime in 1954.

Contrasted to copper, lead and zinc supplies during the past year have become at least adequate. Consumption decreased slightly, while imports greatly aided domestic supplies. Mine production in the U. S. of both lead and zinc was little changed from the previous year. Declining prices for both

metals forced several producers to curtail or completely shut down activities.

Record imports of bauxite helped the aluminum industry to turn out some 935,000 tons of metal last year, for an increase of 12 pct compared with 1951. The million ton peak set for 1952 was not reached because of serious power shortages in the Pacific Northwest and in the Tennessee Valley.

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IRON hobnails and knives about 2000 years old and in a state of almost perfect preservation have been excavated from Roman ruins in Britain, according to information released by Britain's Scientific and Industrial Research Dept. Scientific analysis of the soil disclosed that bacteria facilitating rust were inert. Normally, these bacteria permit corrosion to continue after the first layer of rust has sealed off the metal from the air, because they liberate oxygen underneath the protective coating. Further investigation is reported to have shown that a substance in the soil inhibited bacterial process. The substance was identified as tannin, used in tanning leather. The area, York (Eboracum), had once been a Roman tanning center and bits of leather found in the diggings confirmed the hypothesis. Industrial experiments are scheduled to apply the discovery to underground pipelines and other iron fixtures.

In the U. S., Earle R. Caley, of Ohio State University reported that American chemists were using rust-worn metal relics of ancient Rome to find ways to combat corrosion loss.

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EUROPEAN steel production during 1952 surpassed that of any previous year, with an estimated 109 million metric tons. The statement, offered by the UN Economic Commission for Europe, includes an estimate of Soviet production. The figure represents an increase of 10 million tons over 1951. Significant perhaps is that 42 pct of the total was produced by the Soviet Union and its satellites. During 1951 Russia and its satellites produced something over 41 pct of the total. Western Europe, however, showed an increase of 8 pct, to reach a total of 62,970,000 metric tons. Soviet union production rose 12 pct, while iron curtain nations gained 14 pct. Russia is estimated to have produced about 35 million tons.

Britain maintained her lead as the Continent's top producer, but the German Federal Republic was moving up fast, with an increase of 17 pct over 1951 output. Britain's total output for 1952 was estimated at 16.4 million metric tons, an increase of 3 pct over the previous year. Certain international trends were noticeable in Britain and Germany. Britain became a net importer of steel for the first time, while the outlook for Western Germany indicates that the country will soon import more steel than she exports.

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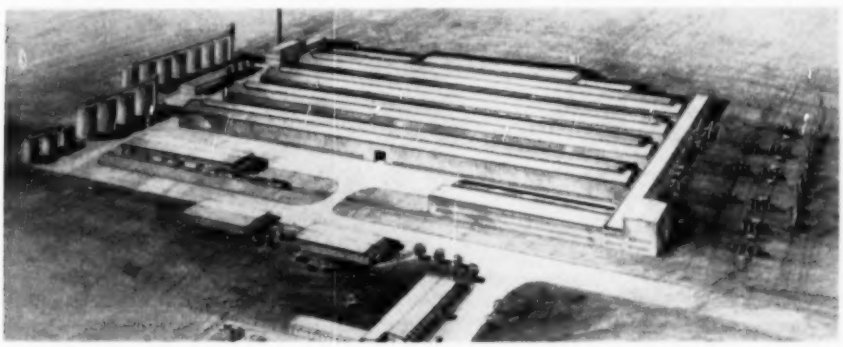
ANACONDA Copper Mining Co. expects to complete its aluminum plant on the Flathead River, three miles north of Columbia Falls, Mont., by mid-1954. The site has already been cleared and detailed designs of the plant are well advanced. The plant is scheduled to produce some 50,000 tons of aluminum annually. Each of two potlines will be housed in two of the four long parallel buildings. Large Soderberg anodes of the vertical pin type will be used. The property lies along the main line of the Great Northern Railway and is about one mile from Bonneville Power Administration's transmission line from Hungry Horse Dam to Hot Springs and Spokane. Electric power will be brought to the reduction works at 230 kv.

The location of the potlines places the direct circuit terminals at the rectifier station. A fifth building on the easterly side will house the casting shop.

Reynolds Metals Co.'s Bayer plant at Corpus Christi, Texas will supply alumina for the Anaconda plant. After unloading from rail cars at the north end of the plant, alumina will be stored in silos. The flux and reagent storage will also be located at that end, along with the paste plant, boiler house and garage.

Shops, storehouse, office, laboratory, change house, and parking lot will be on the westerly side of the plant. Roofed-over area will cover more than 600,000 sq ft, with some 450 men employed in the plant's operation.



The drawing is an artist's conception of what Anaconda Copper Mining Co.'s new aluminum plant will look like when completed. Construction is scheduled for completion in 1954 at Columbia Falls, Mont., with an expected annual capacity of 50,000 tons of aluminum.

Mining Abstracts

During recent months, several articles have been published in MINING ENGINEERING, the AIME Mining Branch publication, that bear on the activities of metallurgical operations. These articles are listed below for the convenience of the reader.

Copies of issues in which individual articles appeared can be obtained from AIME at the single copy price of the magazine, or photostats of the articles can be obtained at the regular prices for such work.

All articles listed have appeared during the year 1952.

January: **Manganese Extraction by Carbamate Solutions and the Chemistry of New Manganese-Ammonia Complexes.** Reginald S. Dean. Manganous oxide is readily soluble in concentrated ammonia solutions containing ammonium salts. Lixiviants of ammonia and ammonium carbamate permit ready extraction of manganese from reduced ores, and the manganese in such solutions may be precipitated by heating to transform the carbamate to carbonate.

February: **Cheaper and Improved Methods of Beneficiating Lower Grade Ores Was Target in 1951.** Raymond E. Byler. Annual review for 1951 of minerals beneficiation projects, with new and improved methods, techniques, and equipment.

Industrial Minerals Set New Production Records. A. B. Cummins. Annual review for 1951 of industrial minerals, with commodity listings.

Diamond Orientation in Drill Bits. E. P. Pfleider. Diamond drill research at School of Mines, University of Minnesota.

March: **Ultra-Fine Grinding and Classification with Fluid Jet Pulverizers.** M. F. Dufour and J. B. Chatelain. Discussion of fluid jet mills for pulverizing solids that could not be processed by other attrition methods because of physical properties.

Contact Angles and Surface Coverage. W. Philippoff, S. R. B. Cooke, D. E. Cadwell. The relationship between surface coverage and the contact angle is extremely important in flotation.

Development of the Disco Process of Low Temperature Carbonization. C. E. Lesher. Development of the process for the production of low temperature coke is described from 1920 to 1949.

April: **Taconites Beyond Taconites.** N. M. Levine. Discussion of the possibilities of utilizing nonmagnetic taconites.

Radiotracer Studies of the Action of Dithiophosphate in the Selective Flotation of Galena and Sphalerite Using CuSO$_4$ and NaCN. C. M. Judson, A. A. Lerew, R. B. Booth, J. S. Kennedy, G. L. Simard.

Chemicals from Coal Hydrogenation. E. E. Donath. Application of the coal hydrogenation process for the production of chemicals is described. It has been estimated that a plant to produce 31,090 bbl per day of chemicals and fuels would cost $326 million. These products would consist of 6.1 pct by weight tar acids, 50.8 pct aromatics, 16.4 pct LPG, and 26.7 pct gasoline.

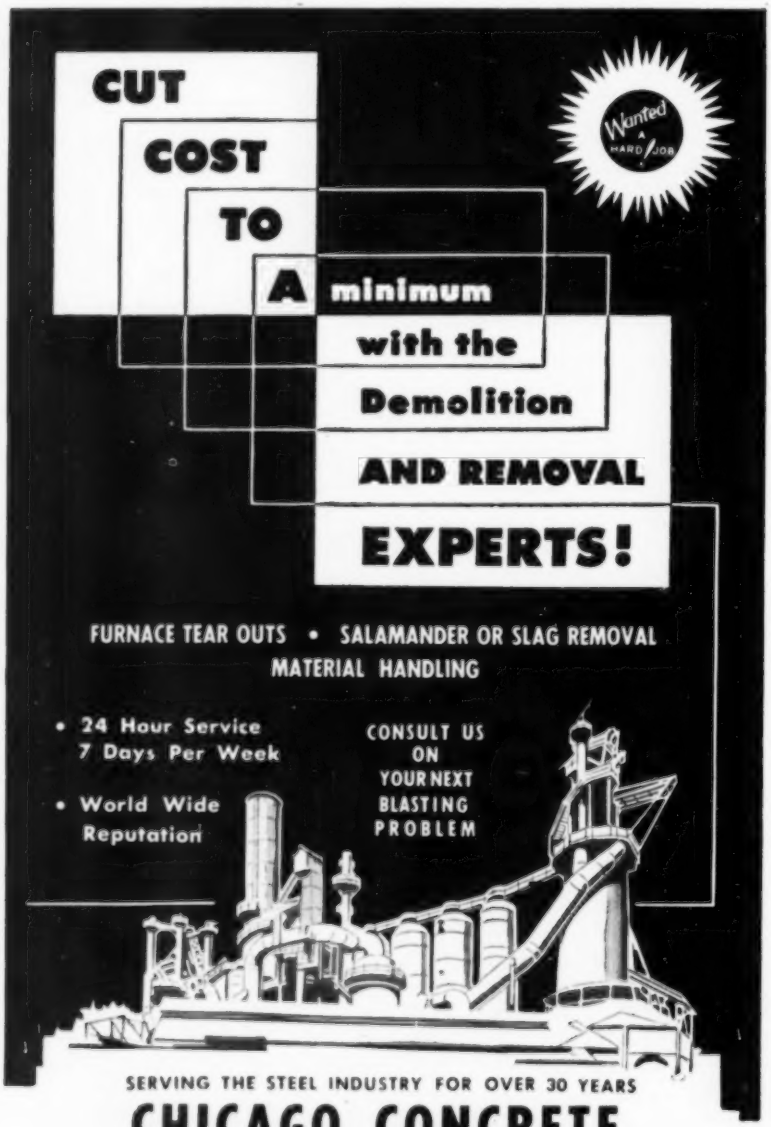
Some Dynamic Phenomena in Flotation. W. Philippoff.

May: **Low Base Metal-High Silver Ores Give Better Smelter Returns with Pre-cyanidation Treatment.** R. R. Ryan.

Chromium Ranks Among the Most Strategic of Metals. Roland D. Parks.

The Third Theory of Comminution. Fred. C. Bond. A new theory of comminution stating that the total work required for crushing and grinding varies inversely as the square root of the product size.

Screened Ore Used for Fine Grinding at Lake Shore Mines. Bunting S. Crocker.



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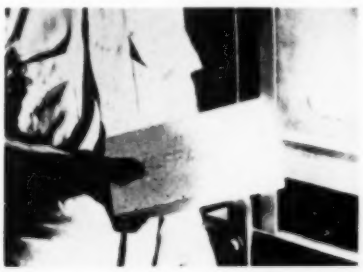
1—REFRACTORY BRICK: Consisting of bubbles, hollow spheres of aluminum oxide specially bonded together, this material is one of the



most heat resistant refractories available. Even though one end of the brick has been heated to over 2000°F, the operator holds it in his bare hand. Alfrax BI brick made by *Carborundum Co.*, has a P.C.E. value equivalent to about 3400°F.

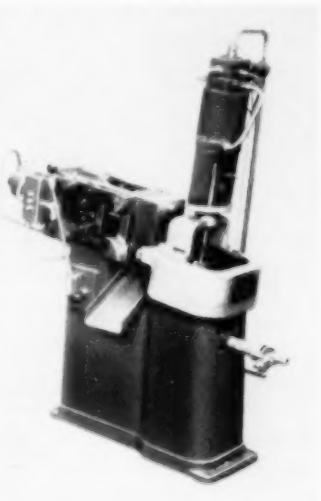
2—SILICONE RUBBER: This medium-durometer rubber remains flexible at −120°F. Designated as SE-550 this silicone rubber is believed to have the lowest change in bending modulus of any commercially available elastomer. It shows less than 25 points durometer increase from 500°F down to −120°F. It is said to outperform all other silicone rubbers at any low temperature while still retaining the heat resistance up to 500°F of most other silicones. *General Electric Co.*

3—INDUCTION HEATING TOOL: A practical working tool for continuously measuring temperature of work during an induction heating cycle is announced by *Leeds & Northrup Co.* Mounted 4 in. from an induction coil the Rayotube can focus on an opening as small as 0.1 in. between turn of the coil and through the opening sight on the hot work.

4—THERMOCOUPLE TUBE: Made of a nickel alloy this thermocouple protecting tube has been introduced by *Minneapolis-Honeywell Regulator Co.* The new alloy is rated at 1900°F having a chemical composition similar to Chromel T.

5—HARDNESS TESTER: Portable tester is designed for a hardness range of 20 to 500 Brinell with maximum accuracy over the full range of the 12 in. gap and 4½ in. throat. *Blosjo Enterprises.*

6—DIE CASTING MACHINE: This IMP/96 1 lb die casting machine contains an injection system of the impact type whereby the piston area for injection is much larger than the area for piston return. Weighing 470 lb and taking up 12x36 in. floor space it is a high speed production machine applicable to a wide range of products. *DCMT Sales Corp.*



7—LOADMETER: A device for controlling wear and limiting breakage of carbide tools has been announced by *Detroit Milling Cutter Co.* The instrument works on the ammeter principle to reflect motor capacity and percentage overloads. It can be set for any motor ranging from 1 to 50 hp. The initial starting surge of a machine pulls from three to five times the running amperage. While an ammeter selected for a given motor size could burn out under this starting load, the Loadmeter, through damping the current transformer provides protection against the contingency.

8—FLOW TEST KIT: A flow test kit for laboratory research and field flow checking work is available from *Fischer & Porter Co.* The kit consists of five Pyrex brand glass Tri-Flat metering tubes with five spherical constant-density floats and instruction handbook.

9—DIE ANGLE SCOPE: An optical instrument designed for measuring entrance angles of wire drawing dies has been announced by *American Optical Co.* It permits reading entrance angles to an accuracy of ±10 min of arc. Every size of carbide wire drawing die can be measured accurately from the largest down to dies as small as 0.005 in.

10—PORTABLE VACUUM PUMPS: Compactly mounted on a fabricated steel base so the entire unit can be transported by truck, fork truck or crane, vacuum pump trucks are available from *F. J. Stokes Machine Co.* These pump wagons are available in two models. The smaller handles more than 2000 cfm between 1 and 10 m absolute pressure and the larger more than 4000 cfm between 1 and 10 m absolute pressure.

11—FORK LIFT TRUCK: A 4000 lb capacity fork lift truck outfitted with a special carriage and attachments to handle nearly a dozen different types of loads has been announced by the *Baker-Raulang Co.* It handles ordinary pallet loads, works as a side shifting truck to spot loads in tight areas, empties drumloads of bulk material by hydraulically tilting drums in a vertical plane, and hauls and stacks drums and tote box loads.

12—FOUNDRY PACKAGE: The chemical div. of *General Electric Co.* has available a four-in-one foundry package of all synthetic materials required for the new shell molding process and for traditional sand casting. A new phenolic resin binder and silicone parting agent are included in the package. Liquid core binder resin and Permafil for impregnating porous castings complete the package.

13—COLORIMETER: Instrument employing transmission type interference filters which provide high spectral purity has been announced by *Bausch & Lomb Optical Co.* Speed and accuracy of determination, plus user convenience through two handy control knobs, are among features of the instrument.

Free Literature

20—TEST SPECIMENS: Test specimens are common metals and alloys mounted and identified, and supplied with photomicrograph, analysis, hardness, etc., for comparison or teaching. *Adolph I. Buehler, Inc.*

21—STEEL DOORS: Complete information on metal doors, sliding bi-pass doors, and B-labeled doors is contained in brochure available from *Virginia Metal Products Corp.*

22—ACF PRODUCTS: Pamphlet issued by *American Car & Foundry Co.* lists products manufactured.

23—TRANSMISSION SYSTEMS: *Fischer & Porter Co.* has released catalog T-50 illustrating pneumatic, magnetic, electric, electronic, and electronic follower equipment.

24—MOLYKOTE LUBRICANTS: Technical information on all standard industrial grades and compositions is available from *Alpha Corp.* A detailed description of this new principle in lubrication and applications is included.

25—INTEGRATOR: Available in single or double counter models, this integrator is described in bulletin issued by *Instron Engineering Corp.* Accurate electromechanical integration, and high speed response long time stability are advantages claimed.

26—SHELL MOLDING: The shell molding process for producing stainless alloy castings is described in booklet published by *Solar Aircraft Co.* The ability of this foundry to produce high quality castings of difficult alloys is described.

27—DIE MATERIAL: Bulletin No. 41 entitled *Meehanite Metal As a Material for Forming and Stamping Dies* has been published by the *Meehanite Metal Corp.* A wide variety of die applications in all types of industry is listed.

28—DESULPHURIZING MOLTEN METAL: Advantages that can be obtained through addition of Solvay dense soda ash to molten metal are summarized in booklet. Details of the advantages and various methods of applications are listed. *Allied Chemical & Dye Corp.*, Solvay Process Div.

29—HI-TEMP OIL: A new lubricant for use at temperatures of 500°F and over has been announced by *E. F. Houghton & Co.* This hot-spot lubricant combines molybdenum disulphide with a synthetic base and a pure low carbon content petroleum oil.

30—CUT-OFF MACHINES: Folder describes the complete Buehler line of cut-off machines. Five models are available for samples from ½ to 3 in. diam. *Buehler Ltd.*

31—MAGNETS: A new chart *What Makes a Magnet* describing natural forces causing magnetism is available from the *Eriez Mfg. Co.* Diagrams and drawings are shown with explanatory captions.

32—EXTRUDED SHAPES: A complete catalog covering more than 4000 standard extruded aluminum shapes, rod, bar, and tubing available without additional die service charge has been released by *Precision Extrusions.* The 98-page book is in five major divisions with 35 subdivisions.

33—ROLLER HEARTH FURNACES: Illustrated bulletin on roller hearth furnaces has been released by *Surface Combustion Corp.* Three principal design types are featured. Related prepared gas atmosphere generators are shown and a chart of prepared atmosphere compositions is included for reference.

34—CONVEYORS: *Jeffrey Mfg. Co.* has reprinted the conveyor section of its general merchandise catalog and presented it as an informative belt conveyor handbook. Many conveyor problems can be solved by using standard conveyors, and this publication illustrates and describes an extensive line of standardized units.

35—ELECTRIC FURNACES: Described in a new bulletin is the Speed Treet electric furnace, designed to heat treat high speed steels where temperatures up to 2600°F are required. *Hevi Duty Electric Co.*

36—TESTING MACHINE: Bulletin 4204 describes and illustrates new improved models of Baldwin 60-H and 12-H low cost universal testing machines. *Baldwin-Lima-Hamilton Corp.*

37—AUTOMATIC RACK MACHINES: Complete descriptions and illustrations of the *Frederic B. Stevens, Inc.* automatic rack type machines are contained in bulletin 61. Many special applications of these machines are also illustrated.

38—HYDRA SPRING: This new Wales hydra spring uses compressible fluids to produce spring pressures up to 3800 lb. It is ideal for stripping actions in all types of dies. *Wales-Strippit Corp.*

39—TAPECOAT GUIDE: Brochure designed to help solve corrosion problems has been released by the *Tapecoat Co.* Details on how and where coal tar protection can be used to best advantages and case histories are included.

40—WORTHINGTON: Story aimed to better acquaint people with the firm, a booklet entitled *A Lot of Things Beside Pumps* has been released by *Worthington Corp.*

41—CONVERSION TABLES: A wallet sized card giving approximate relationship between Brinell, DPH (Vickers), Rockwell, and Shore Scleroscope hardness values and corresponding tensile strengths of steels is available from *International Nickel Co.*

42—DRUM SEPARATORS: Permanent nonelectric magnetic drum separators for the removal of ferrous materials from chemicals, minerals, and other materials are described in booklet issued by *Eriez Mfg. Co.*

Journal of Metals
29 West 39th St.
New York 18, N. Y.

March

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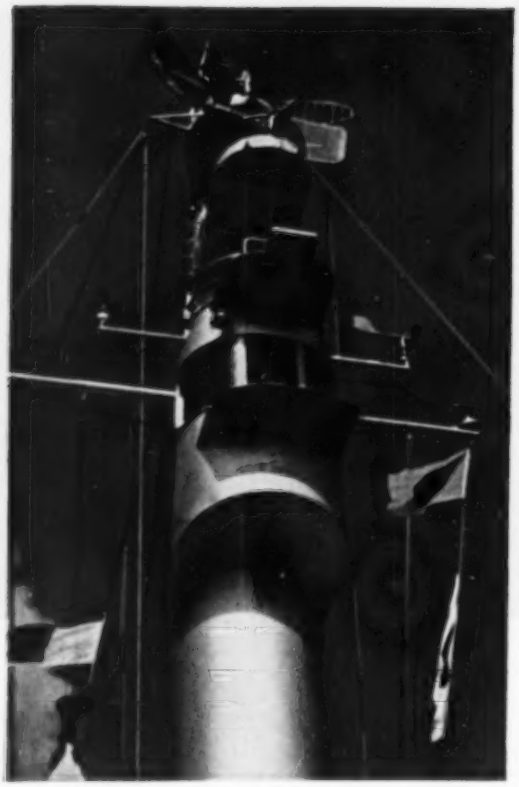


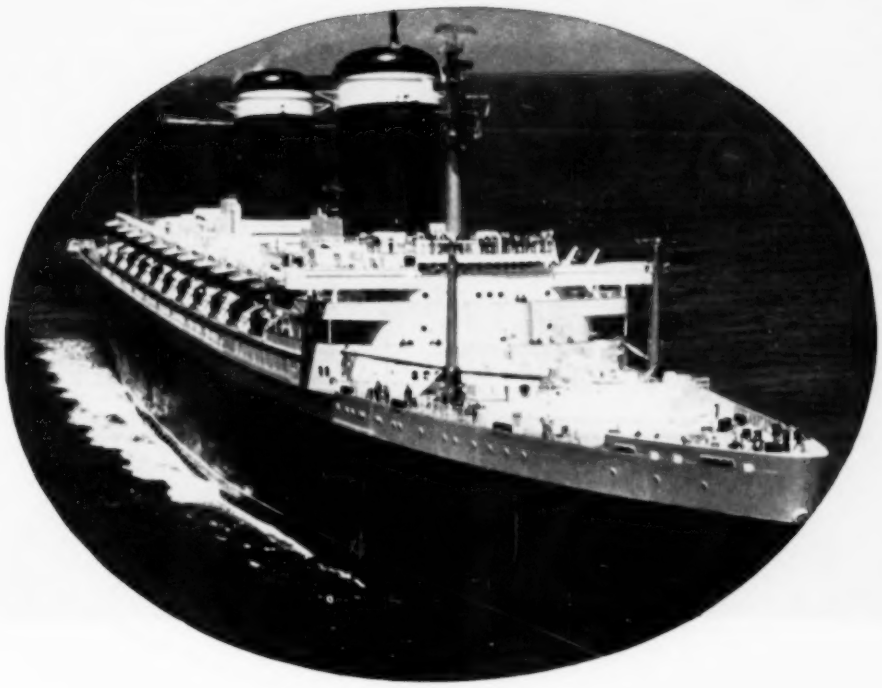
Dramatic radar tower of the S. S. United States. The ship was designed by Gibbs & Cox, Inc., built by Newport News Shipbuilding and Drydock Co., and is operated by U. S. Lines, Inc.

S. S. UNITED STATES MADE WITH BRICK!

Symbol of superiority among the world's merchant marine fleets. The fastest and safest passenger liner afloat. Flagship of American production . . . made with brick.

Refractory brick, that produced the thousands of tons of steel for the mighty S.S. United States. For her gigantic hull and the thousands of components . . . all made from steel, the metal that has established America as the industrial leader of the world.

In every type of furnace used in a steel mill, you will find refractory brick produced by GREFCO. The coke ovens that make the fuel for blast furnaces are built of silica and fireclay brick, while coke chutes and hoppers give trouble-free service when lined with CARBEX silicon carbide. A long-time standard of quality in coking chambers is GREFCO's silica brick. The same eminent position is occupied by GREFCO fireclay brick in other parts of the ovens. Both GREFCO silica and



fireclay brick are produced in strategic locations throughout the country.

In blast furnaces it's OLIVE HILL all the way. Hard fired, dense OLIVE HILL, a special high duty fireclay brick for which GREFCO is famous, provide the best of service in hearth, bosh and stack. Other GREFCO high duty fireclay brick are used in lining piping and other auxiliaries.

Most hot blast stoves are lined with dense, high duty fireclay brick but, for extra severe service, the combustion zone inner lining, the dome, and the top checkers, are built with HIAC or SUPERAC, super duty fireclay brick.

GREFCO's exclusive unburned RITEX basic brick and STEELKLAD, a basic brick permanently jacketed in a patented steel shell, give unmatched service in the open hearth.

In every other phase of steel production, GREFCO products will be found. There would be no S.S. United States without steel . . . and there would be no steel without refractory brick. If, in your production, you demand quality refractories backed by the most modern of research facilities . . . available in whatever quantity you may require . . . call on GREFCO for a truly *complete refractories service.*

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Advertisement

ELECTROMET Data Sheet

A Digest of the Production, Properties, and Uses of Steels and Other Metals

Published by Electro Metallurgical Company, a Division of Union Carbide and Carbon Corporation, 30 East 42nd Street, New York 17, N. Y. • In Canada: Electro Metallurgical Company of Canada, Limited, Welland, Ontario.

Why 3 Per Cent Chrome Steel Makes Good Castings for Wear Resistance

Castings of 3 per cent chromium steel have been used in substantial tonnages, for many years, for various equipment parts demanding good wear resistance. Such castings offer an excellent combination of hardness and toughness. Typical applications are crusher parts used in rock- and ore-crushing equipment, swing hammers for pulverizing coal, railroad switch frogs, gears, pulleys, sheaves, and other castings that must meet severe conditions of wear.

Fig. 1. Railroad switch frogs, which are subject to severe wear, give outstanding service when cast of 3 per cent chromium steel.

The 3 per cent chromium steels, are normally produced in a carbon range of 0.30 to 0.50 per cent. They exhibit excellent depth-hardening properties, which simplify heat-treatment and insure uniformity throughout heavy sections. The analysis is usually modified by a molybdenum addition, since this element aids in increasing hardenability.

Fig. 2. Grating for top of shake-out machine is cast of 3 per cent chromium steel to give good wear resistance and long life.

Properties Improved by Heat-Treatment

The best properties of 3 per cent chromium steels are developed through heat-treatment. Generally, this consists of a normalizing treatment from 1650 deg. F., followed by tempering in a range between 1000 and 1250 deg. F., depending on the physical properties desired. Double normalizing is sometimes used to obtain further improvement in the grain structure. With carbon on the high side of the specification, air-quenched castings show a Brinell hardness number of over 400 in 3-inch sections. This hardness is practically uniform throughout the section. Oil quenching is employed to produce higher hardness and depth of penetration, and even in a 4-inch section, a hardness number of over 500 Brinell is obtained.

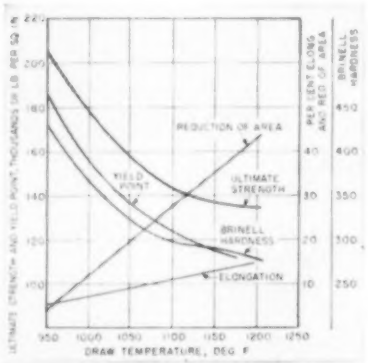


Fig. 3. These curves show the response to tempering of a 0.37 per cent carbon, 2.93 per cent chromium, 0.35 per cent molybdenum steel previously normalized from 1650 deg. F.

The steel also shows good response to tempering. After a normalize and a 1100 deg. F. treatment, it has a tensile strength close to 150,000 pounds per square inch, with an elongation value of about 12 per cent, and a Brinell hardness of about 300. When greater ductility is required, tempering should be done at higher temperatures. However, in such instances, some strength and hardness are sacrificed.

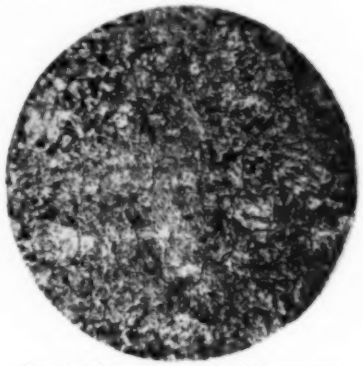


Fig. 4. Photomicrograph of 3 per cent chromium steel normalized from 1650 deg. F. and tempered at 100 deg. F. (X250). The pseudo-martensitic structure is well suited to resist abrasion.

Effect of Other Alloy Additions

Molybdenum in the range from 0.30 to 0.50 per cent will improve depth-hardening characteristics and aid in reducing susceptibility to temper brittleness in the lower temperature ranges. If the molybdenum-bearing steel contains relatively high carbon (0.40 to 0.60 per cent) additions of approximately 0.08 to 0.10 per cent vanadium provide greater uniformity in hardening. Small additions of silicon increase strength and hardness and this element is sometimes increased to 0.80 or 1.00 per cent. Manganese is added in amounts between 0.50 and 0.80 per cent.

Metallurgical Service Available

When you have occasion to produce castings for applications involving severe abrasion and wear, it will pay you to investigate the advantages of using 3 per cent chromium steel. If you need help on some specific metallurgical problem, be sure to consult one of ELECTROMET's specially trained metallurgists and engineers. For further information, write to the nearest ELECTROMET office: in Birmingham, Chicago, Cleveland, Detroit, Los Angeles, New York, Pittsburgh, or San Francisco. In Canada: Welland, Ontario.

The term "Electromet" is a registered trademark of Union Carbide and Carbon Corporation.

Drift of Things

WHEN the atomic age broke suddenly upon the world in 1945 with all its terrible implications, predictions concerning the future of atomic energy were as numerous as columnists and often inflated. Today, some seven years since the explosion and probably ten since the Government took over development of nuclear energy, the impact on our way of living has been largely political (except of course for the thousands of people who have become employed in the AEC). Considering the world situation, weapons have come first naturally. But credible progress in the plowshare uses of nuclear energy—medicine, agriculture, power—can also be noted.

The point of this is that Atomic Energy Commission people and our Congressmen, saddled with the awful responsibility of administering and developing the new force, are and have been studying the whole program critically. The big question is whether or not the United States is doing the best it can to harness the energy of the atom. Inextricably tied up in this question is the problem of secrecy for security. America is proud of its industrial know-how which comes part and parcel from the vast reserve of skilled workers, scientists, engineers, and administrators, the product of the system of universal education. It comes from the human desire of the people who have applied their energies over many decades to harvest the resources of our fertile land for homemaking, for comfort, and, when the need has arisen, for self-defense.

Out of fear of the inimical Soviet, protective secrecy has prevented full utilization of this know-how. Many of those intimately connected with the atomic energy program feel that much information, the fruit of billions of dollars spent on research and development, with care can be declassified so that industry can harness nuclear energy for peace. Efforts of the Commission in this direction are bringing the fruits of the Atomic Age closer to reality.

An Advisory Committee on Industrial Information, made up of engineer-editors representing every industry possibly interested, has been functioning for some time. This group has received top security clearance so that it can perform its function of studying atomic energy developments, and processes for possible applicability in industry. The committee has authority only to indicate what information would be useful to industry so that the Commission's security group can consider it for possible declassification and publication in the industrial press.

In the new Congress, the constituency of the various committees is being worked out. The Joint Committee on Atomic Energy is one of these. The rate of progress of the atomic energy program will rest in the hands of this committee. For it political considerations should be waived so that a selection may be made from men of wisdom.

EFFORTS directed at stimulating interest in careers in engineering among high school and college students are taking hold judging from activity in the New York area and the national "Engineers Wanted" campaign sponsored by the Advertising Council. The New York Section AIME has just completed a two-day guidance program for over 175 students from colleges in the vicinity. This program followed the pattern of one held in 1952 by the St. Louis Section. Included in the program was a panel of industry representatives for each branch of the mineral industries which described types of work and career possibilities. Field trips to mines, a copper smelter, and the Fairless works of the U. S. Steel Co. followed discussion. As at St. Louis, all expenses of the students were paid by the Section. This type of interest manifested by future employers in young men goes a long way toward attracting students to the fields of engineering for which such programs are arranged.

Another indication of industry interest in recruiting engineers was the splendid support received from companies for the new edition of the Mudd Fund's "Careers in the Mineral Industries" being published this month by AIME. This support has made it possible to make the booklet more attractive and to give it wider dissemination than would have been possible using only the contribution of the Mudd Fund which has customarily financed this publication.

An exceptional effort is being made in the "Engineers Wanted" campaign of the Advertising Council. The campaign is well planned and it is clearly described in the illustrated booklet "How Your Company Can Help Promote Engineering as a Career." By directing the booklet to the corporations to carry on the campaign, a sound approach is taken because they have the most at stake.

There is no lost motion because each corporation can push the type of engineering which is most important to it. It is as basic as assuming a role in community activities. To mention just a few of the things to be done which are described in the booklet: Distribute pamphlets on vocational guidance and motion pictures on industry stories or job opportunities to schools and the PTA; cooperate with schools in developing posters and other promotional material; present awards and medals in engineering and science; provide speakers for guidance panels for schools, PTA, and other clubs; send representatives for job interviews.

The program is so workable that many corporations are certain to participate. This places an obligation and even some pressure on the mineral industries to get busy. Other professions and businesses have syphoned off many of the fine young people graduating from our schools because they are frequently in the limelight. Interest in engineering is mounting not only because it actually does have such fine career possibilities but also because of the effort of the Engineering Manpower Commission and company recruiting. The mineral industries must look out for its own in this overall campaign for engineers.

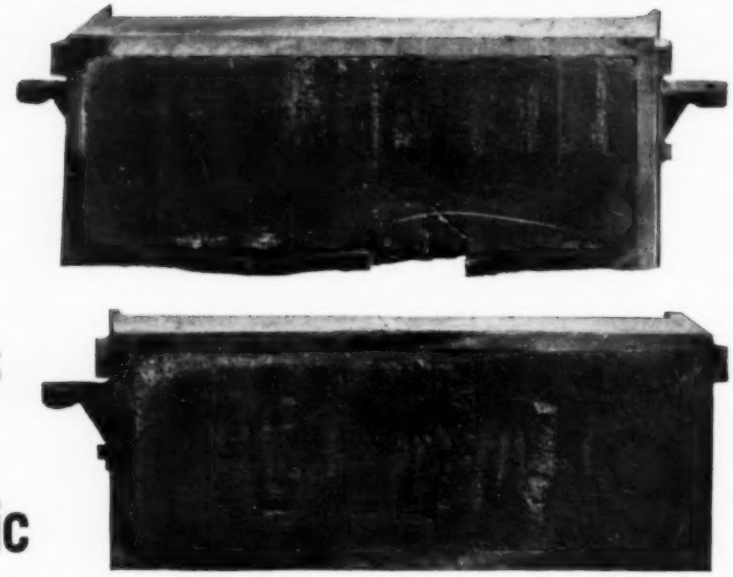
FOLLOWING is a clipping from the *Mining and Scientific Press*, Nov. 2, 1907, sent in by Mr. Ernest Blessing, Miami, Okla.:

"The current idea that uranium ores derive their value from their content of radium is probably due to the fabulous value ascribed to radium in many publications—a value based, perhaps, upon prices paid for it as a chemical and physical curiosity, since they are not justified by any uses thus far found for it. The principal known deposits of uranium ores in this country are in Colorado, where carnotite and uranite (or pitch-blende) furnish the product. . . . Experiments made with the metal as a steel-hardening material do not show that any particularly valuable qualities are added to the steel that are not given by the use of other elements that are at present cheaper. Uranium in the form of an acetate is used as an indicator in various determinations in organic chemistry, and other salts are used in iridescent glass and pottery glazes."

We are fascinated by the powers "ascribed" to the press of those days.

John V. Beall

Ductile Iron Furnace Doors now used by General Electric



The Ductile Iron Door (lower photograph) is still good, as you can see, after three months of use on a steel forging furnace that operated with interior temperatures as high as 1950°F. After one week in same service, the gray cast iron door (upper photograph) is, obviously, ready for the junk heap.

Last 50 times longer...

At General Electric Company's River Works, West Lynn, Massachusetts, steel forging furnaces operate with interior temperatures as high as 1950°F.

Heretofore, gray cast iron door frames of these furnaces deteriorated from growth, warpage and scaling in about six days . . . and cost plenty in terms of down-time, replacement, and week-end overtime for repairs and maintenance.

Seeking a remedy, General Electric tried Ductile Iron door frames, cast by TAYLOR & FENN COMPANY, Windsor, Connecticut. And the result? Average life of these Ductile Iron doors is now estimated at about 300 days. Even though only seventeen furnaces reap this benefit, savings therefrom are estimated at $25,000 per year.

Ductile Iron provides oxidation and growth resistance to an extent heretofore unavailable in gray iron castings for furnaces, engines and other equipment subject to elevated temperatures.

High temperature applications of Ductile Iron castings include forging furnace door frames, sintering grate bars, pouring troughs, lifting plates for coil annealing machines, lifter bars in rolling mills, and scores of other parts subject to heat.

AVAILABILITY—Send us details of your prospective uses, so that we may suggest a source of supply from some 100 authorized foundries now producing Ductile Iron under patent licenses. Request a list of available publications on Ductile Iron . . . mail the coupon now.

INCO

The International Nickel Company, Inc.
Dept. 20, 67 Wall Street, New York 5, N. Y.

Please send me a list of publications on: DUCTILE IRON.

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THE INTERNATIONAL NICKEL COMPANY, INC. 67 WALL STREET NEW YORK 5, N.Y.

The first plant to produce zirconium and hafnium on a commercial basis is being designed by the Rust Process Design Co. Rust, a new subsidiary of Carborundum Co., recently signed a five year contract with the Atomic Energy Commission for delivery of 150,000 lb of zirconium and hafnium sponge metals annually. The plant is being built for Carborundum at a cost of $2.5 million.

One of two lead furnaces at the Herculaneum smelter of St. Joseph Lead Co. is being closed. The furnace will be idle for a number of months and in July the other furnace will be closed while new sintering equipment is installed. The Herculaneum plant has been turning out the equivalent of about 8000 tons of refined lead per month with both furnaces operating.

The U. S. will get an additional 22,000 tons of aluminum to be delivered during February and March under an agreement with Great Britain and Canada. DPA officials said the loan will aid in offsetting the loss brought about by recent power shortages. It will be repaid during 1954 and 1955.

Apex Smelting Co. formed the National Metallurgical Corp. for construction and operation of a pilot plant for production of aluminum-silicon metals from clay. American Smelting & Refining Co. has a 50 pct interest in the new firm. Operation is expected to begin by June 1, 1953.

British Columbia base metals industry is suffering from a 1952 summer drought which has seriously curtailed power supply. The smelting and refining plants of Consolidated Mining & Smelting have cut operations 30 pct.

DuPont is expanding titanium sponge production facilities at its Newport, Del., plant and is scheduling increased output at its Edge Moor, Del., plant. The expansion, at Government request, will yield an estimated 13,500 additional tons of titanium sponge during the next five years. New units to be erected at Newport include a main manufacturing building, power house, office building, laboratory, finishing building, and change house.

The nation's seventh aluminum producer will be the Wheland Co., according to DPA plans. Wheland currently manufactures a complete line of oil well drilling equipment and has a foundry div. making automobile castings. The company plans to build two plants, one in a coastal area and the other in the Tennessee Valley. The first will make alumina and cost about $20 million. The other plant will manufacture aluminum. Construction cost is estimated at about $50 million.

The U. S. Government has entered into an agreement with two M. A. Hanna Co. subsidiaries for production of ferronickel from deposits on Nickel Mountain in Oregon. Hanna Coal & Iron Co. will develop the mine at its own expense and will produce a minimum of 95 million lb of nickel. The agreement with Hanna Nickel Smelting Co. provides for $24.8 million for construction of a smelter.

Molten aluminum is poured into pigs at an aluminum reduction plant.

Aluminum Industry

Expands For War and Peace

by Samuel W. Anderson

THE basic raw material for production of aluminum is bauxite, although some day it may be possible to utilize such leaner ores as anorthosite. Domestic resources of bauxite are quite small. Prior to World War II, the industry's domestic bauxite resources were the limited high grade deposits in Arkansas. At that time, the reserves of suitable domestic ores containing in excess of 55 pct Al_2O_3, were estimated at approximately 9 million tons. Accordingly, the industry learned to rely increasingly upon foreign sources of bauxite, chiefly Surinam, which was developed by Alcoa when it was the only producer. The Canadian industry, in turn, had relied heavily upon similar deposits in British Guiana. As a consequence of the losses in the bauxite fleet during World War II, a process, known as the soda, lime, sinter process, was hastily translated from laboratory to production stage in 1943. With it the high silica bauxites of Arkansas, theretofore considered unsuitable, could be treated to develop an acceptable plant feed. Deposits of lower grade ores of a silica content as high as 15 pct and with appreciable iron content were thus opened up as a possible raw material during the emergency.

As a consequence of this successful project, the presently estimated reserves of utilizable ores in Arkansas have risen to about 50 million tons, still not a large figure in relation to future demands. In this period considerable experimental work was initiated with respect to the monohydrates in Jamaica and some of the other Caribbean Islands. While the existence of these bauxites had been suspected for some time, no active interest was shown in them until the war and postwar period. Beginning in 1946, extensive experimental work was carried out on the Jamaican deposits by the Aluminum Co. of Canada, Reynolds, and eventually Kaiser. This work was successful and there is now an economic method for processing the Jamaican ores, the reserves of which are very large and as yet not fully measured. Similar work is going on with respect to the deposits in the Dominican Republic and Haiti. Thus, as a consequence of war and postwar research and development, this country is in a far better position than ten years ago. The estimated available reserves in Surinam are of the order of 50 million tons and those of the Caribbean Islands probably in excess of 350 million tons. These supplies, on the basis of roughly four tons for each ton of aluminum will carry the aluminum industry at even rising rates of production for many decades. Very large deposits are known elsewhere in the world, such as Brazil, but are presently less accessible. Thus, it appears that the aluminum industry of the Western Hemisphere does not have to fear any scarcity even in the presently acceptable grades of raw material for a

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great many years. By that time, it is almost certain economic processes for recovery of aluminum oxide from the non-bauxitic materials will be perfected.

It has been the consistent practice of American industry to bring bauxite from abroad or from local mines to alumina plants in the U. S. Alumina plants are located at Mobile, Baton Rouge, Corpus Christi, East St. Louis, and two in Arkansas. This traditional movement is in part dictated by a $5 per ton tariff on alumina, thus discouraging the construction of alumina plants at the location of the bauxite and in part by the greater ease of handling bauxite than very fine alumina. The bauxite tariff is 50¢ a ton.

About two tons of better grade bauxites are required to make one ton of alumina. At the alumina plants the bauxite is ground, treated with lime, soda, and water in a digester and then, following the blow-off tanks, is put through a filter press and coolers into a precipitator, whence it proceeds to a thickener, followed by filtration and drying through rotary kilns. It is then ready for shipment to aluminum reduction plants. An alumina plant consists largely of tanks and piping. A typical alumina plant of a capacity of 1000 tons of alumina per day will cost, at today's prices, between $40 million and $50 million. Considerable quantities of steam are required, but only relatively small amounts of power.

Aluminum Reduction

Aluminum reduction plants are located primarily in relation to the availability of cheap power, as approximately 9 kw-hr of power are consumed in the production of 1 lb of aluminum. The industry's earliest plants were near Massena, N. Y., followed by those in the Tennessee Valley where Alcoa originally developed its own power, now supplemented by power from TVA, for that company, as well as for Reynolds. During the war several large aluminum plants were built in the Pacific Northwest by the Government and more recently Alcoa has added a new plant at Wenatchee. Approximately 30 pct of projected aluminum production will come from the Pacific Northwest, utilizing both firm and interruptible hydro energy. More recently, an aluminum industry has been established in Texas and Louisiana, utilizing natural gas as a fuel. Natural gas is either burned under boilers for generation of steam in the traditional manner or burned in gas burning engines which drive a series of small direct current generators. One of the new plants just starting up will eventually utilize Texas lignite. It is planned to extract a portion of the volatile tars as a byproduct before using the lignite as a fuel for thermal power generation.

The process of reducing alumina to aluminum consists of dissolving the alumina in a molten bath of cryolite and reducing the metal by use of carbon electrodes conveying power to the pot. It is a continuous process and while it sounds simple, does embody a good deal of tricky art to obtain high efficiencies. In the last ten years great progress has been made in improving efficiency of the reduction process. One school of thought believes that very much higher amperage than used prior to the war improves efficiencies. In addition, the sizes of the pots have been considerably enlarged in recent years. Furthermore, during this decade the European-born Soderberg Process has been increasingly employed in the U. S. This process introduced a continuously fed carbon paste as an electrode which bakes as the electrode moves to its point of consumption.

Sodium alumnate solution is pumped into a large tank for cooling after pulverized bauxite has been treated with a hot caustic soda solution.

Before turning to the outlook for aluminum and its potential market development, it would be well to mention a number of important questions which influence the economics of this industry.

Power An Important Factor

Large quantities of power are needed in the reduction of alumina to aluminum. Every pound of aluminum is a storehouse of 9 or 10 kw-hr and it has frequently been referred to as *packaged power*. If the price of aluminum is to be kept down to stimulate use, it is obvious that the industry must continue to enjoy large quantities of cheap power. The history of the industry suggests that where it is initially established in cheap power areas it does well economically until the availability of that power attracts competing loads which can afford to pay higher prices. This was the case in northern New York state where the growing demand for power for all uses made it virtually impossible to operate economic aluminum plants in this area except under forced draft of Government power subsidies such as the present situation. This same tendency is visible today in the Tennessee Valley. Rates for power in this area have shown a rising trend. This was to be expected as industries moved into the area, attracted by the availability of power. It seems doubtful that the trend will change in the Tennessee Valley. The TVA will soon generate over half of its available power from thermal plants which must rely upon more distant coal, requiring increasing freight rates to the power plants. Significant future addition to aluminum productive facilities of the country are not expected to be located in the Tennessee Valley relying upon TVA power.

The Pacific Northwest situation is more complex, but simply stated the development of power in that area over the next few decades will probably require larger capital outlays per kilowatt installed than has been the case in the past, whether or not such ex-

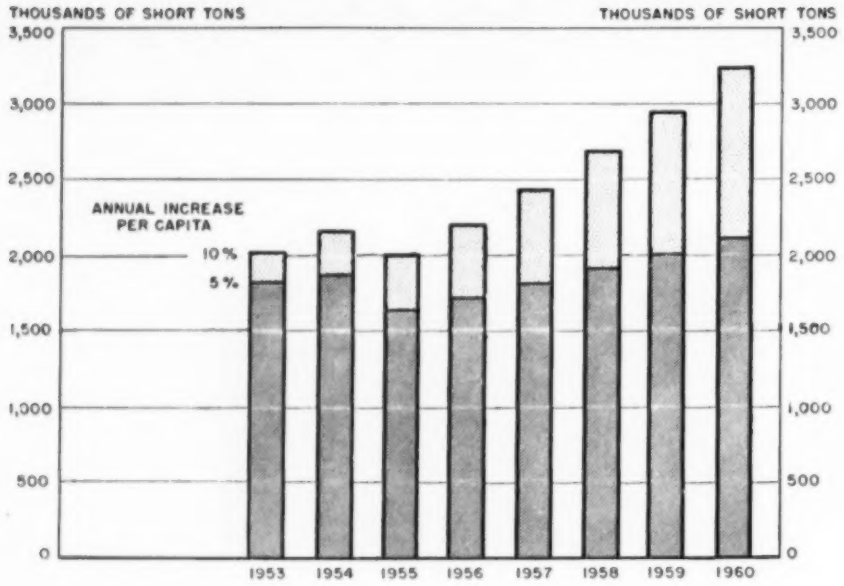


Fig. 1—According to estimates, peak military aluminum requirements have been passed. Bars represent combined military and civilian requirements for aluminum. Trends indicate civilian demand will grow at a rate of 5 pct per capita annually. An increase of 10 pct is also shown.

penditures are made by private industry or by the Government. It is, therefore, fair to expect that average rates in the Pacific Northwest, at least for firm power, are likely to show a rising tendency. The heavy power users such as aluminum and magnesium may experience difficulties in holding their costs down. For many years until adequate storage is built for the Columbia River system, seasonal power, reliable in the summer but unreliable in the winter, will be available in large quantities over and beyond the firm generation. If some day repeated aluminum crises can be prevented through a large stockpile, further expansion in this area might be attractive if interruptible power rates can be established at a sufficiently large differential under the ruling firm power rates. It may pay a producer to contemplate seasonal shut-downs, averaging out at not too serious an aggregate amount over a period of years, if his power rate is correspondingly lower for such interruptible power. Today Bonneville's interruptible power rate is identical with its firm power rate.

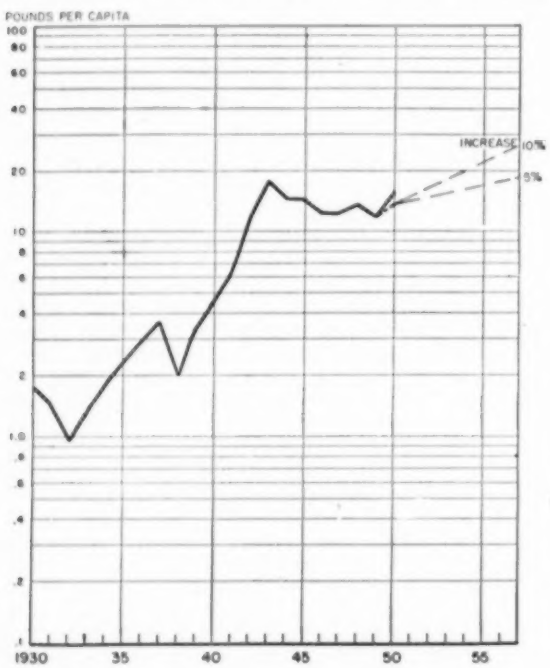


Fig. 2—Estimated per capita consumption of aluminum by 1962 would be about 27 lb, based on a 5 pct per year increase, contrasted with 13½ lb in 1950. Consumption figures include secondary aluminum made from scrap.

The future expansion of the American aluminum industry is likely to occur more in areas unattractive for general industrial development. In Alaska, large and cheap hydroelectric power resources can be enjoyed for a century or so without danger of having the energy diverted. Alcan is developing a project of this kind in Western Canada and Alcoa has announced a large developmental plan of similar character for Alaska. Another possible area for development of reliable long-term cheap power is through use of coal in thermal generation, close to the enormous, rich coal beds in the Ohio River Basin. This will presumably have to take the form of captive power plants of the highest efficiency using very large machines. New low temperature carbonization schemes, to be tried for the first time on Pittsburgh seam coal by Olin Industries, in partnership with Pittsburgh Consolidation Coal Co., may be employed.

Another factor inextricably bound up with the location of aluminum reduction plants is in and outgoing freight costs. These must be skillfully balanced with area advantages in respect to power costs. The largest portion of the aluminum market lies in the east-central part of the U. S., although consumption in the west is growing. Since the aluminum producer pays freight on sales of aluminum pig and ingot, the closer his customer, the greater his financial advantage. He must also consider freight haulage in of bauxite or alumina, as well as cryolite, petroleum coke, pitch, soda ash, lime and the like. Transportation costs have a tendency to offset relatively cheap power costs in the Pacific Northwest. Much of the metal or its fabricated forms must move to the east. The Pacific Northwest also is relatively

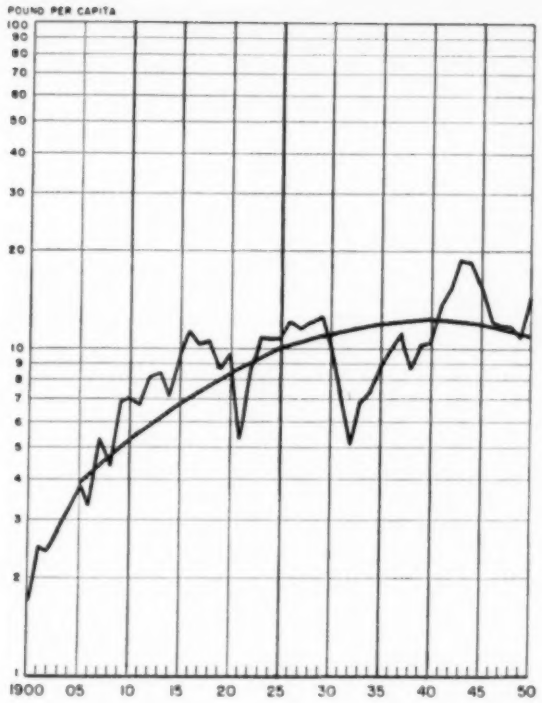


Fig. 3—Here is a history of per capita consumption of zinc between 1900 and 1950.

far from the customary locations of the alumina plants around the Gulf of Mexico.

Production and Consumption

Looking into the future an attempt can be made at analyses of the markets in relation to supply. Twice during the past decade an aluminum crisis has been generated by war or defense programs. In each case, the country found itself very short of aluminum and with virtually no stockpile. Under sponsorship of the Government, very rapid, large expansions were undertaken. During the war, this expansion was largely financed by the Government and because of the power shortage, plants had to be located in such uneconomic spots as New York state, New Jersey, and Southern California. Three of these plants, with an aggregate capacity of 360,000 tons of aluminum had to be abandoned after the war. The total expansion during World War II was 735,-000 tons. The Korean period was entered with a capacity of approximately 692,000 tons per year, all owned by three producers. Since then, the Government has authorized expansion programs aggregating 863,000 tons, including the recently announced 200,000-ton expansion. This, together with company reactivation and expansion of approximately 195,000 tons, will give, when completed, primary aluminum capacity of 1.75 million tons. Together with generated scrap and expected normal imports from Canada, this will provide a total metal supply, both primary and secondary, of about 2.2 million tons per year. All of this expansion has been undertaken with private capital, government guarantees in financing unnecessary except in one instance.

It would be well to examine some guesses as to the future demand. Fig. 1 shows in simplified form the best judgment of the average outlook for the balance of this decade. The bars represent a combination of the expected military requirements and the estimated civilian consumption. It is impossible to divide the bars to indicate the relative share of the military and civilian, as the former is classified data. It may be said, that estimated peak requirements for military purposes have probably occurred and will be followed by a somewhat lower requirement in 1954. Beginning in 1955, it is presumed that the military needs for aluminum will decline during two years to something like one third to 40 pct of the 1952 peak. This need will cover non-war attrition and obsolescence of existing items.

The trend indicates civilian demand for aluminum will grow at an average annual rate of about 5 pct per capita from the 1950 pre-Korean consumption. This will obviously not occur in a smooth upward curve. It seems more sensible to base these estimates on an average over a period of time, than to attempt to forecast the inevitable wave motions of business activity and demand.

In reaching this estimate, cognizance has been taken of the fact that the history of consumption of other metals clearly shows that as the metal comes into wider use, the percentage rate of increase in its consumption usually tends to fall. This can be expected to occur in the case of aluminum over an extended period of time, but it seems that it is reasonably sound not to attempt to allow for this factor over such a short period of seven or eight years. Some of those who know aluminum well believe that an estimate of an increase of 5 pct per annum per capita is too conservative. The chart has been constructed to show what the demand

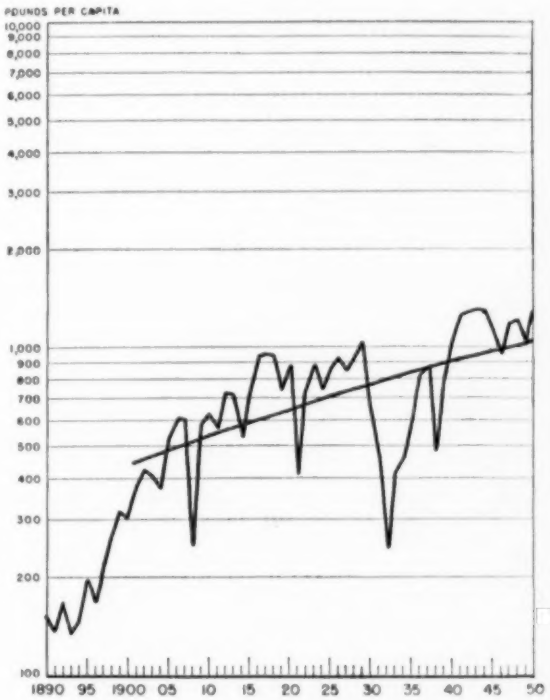


Fig. 4—The tremendous rise in steel consumption between 1890 and 1950 is indicated in this illustration of apparent consumption of steel ingots and castings per capita annually.

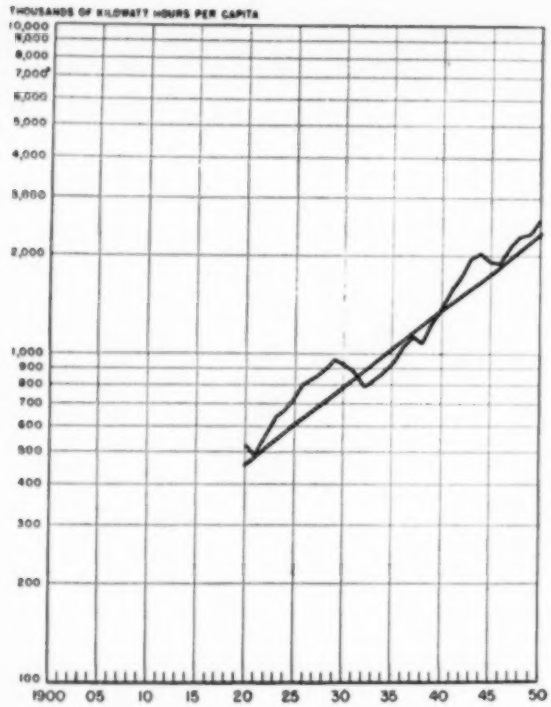


Fig. 5—The estimated apparent consumption of copper between 1900 and 1950.

would be if consumption should rise at a rate of 10 pct per annum per capita.

Figs. 2, 3, 4, 5, 6 depict the history of the per capita consumption of aluminum, zinc, steel ingots and castings, copper, and electric power respectively. Since these charts are all drawn on arith-log scales, it is possible to judge visually the comparative slopes of a 5 and a 10 pct increase per capita per annum. A 5 pct increase will double the per capita consumption in about 13 years. This would mean that by about 1962 the per capita consumption of aluminum would be something like 27 lb, as contrasted with about 13½ lb in 1950 as shown in Fig. 2. This latter figure is corrected from the actual consumption of over 16 lb in 1950 to discount the impact of the Korean outbreak. It should be pointed out that the consumption figures include secondary aluminum made from scrap. Some quarrel with this method, saying that scrap and secondary should not be included, since it has been put into the system once before being taken into account again in consumption. Either method is equally valid, provided it is understood and consistently utilized and provided no significant judgments are made between per capita consumption figures of two metals computed on inconsistent bases.

Potential Uses of Aluminum

Any estimate of the future civilian use of aluminum is hazardous. There are many future events which might greatly affect this estimate both favorably and unfavorably. There are several large potential uses of aluminum which one can see dimly today, but which have not yet become major factors on the demand side of the equation. The more important of these are the following:

The automobile business—The amounts of aluminum in present passenger automobiles is about 22 lb per car and in trucks about 27 lb. The automobile companies, in planning for the future, have either actually designed or are contemplating designing experimental cars of much lighter weight which would embody far larger amounts of aluminum than are presently used. One manufacturer has an experimental model which is said to have over one half ton of aluminum incorporated in it including the engine. If trends toward lightness, higher power, greater deceleration for safety's sake and other considerations take hold in the automobile business, and should automobile companies decide it would be safe to design large quantities of aluminum into their cars, the impact could be very heavy. If the car of the future had 500 lb of aluminum in it, this industry would, on a 5 million car year (here again, estimating is hazardous) consume 1.25 million tons of aluminum. This alone would be over 60 pct of the total metal supplies now in sight, including scrap and imports. Perhaps this is an extravagant *guesstimate*. It does not, however, seem impossible.

Tin can containers—Tin can containers of all kinds in the U. S. consume approximately 3.8 million tons of steel in the form of tinplate. Whether aluminum captures a considerable part of this market depends upon success of experimental work in developing an aluminum can at a competitive price. Unlike the so-called *tin* can, the aluminum can would have a salvage value as scrap. Since some 30 to 40 pct of the cans of the country are used by institutional or other commercial buyers, as distinguished from housewives and scattered buyers, it is

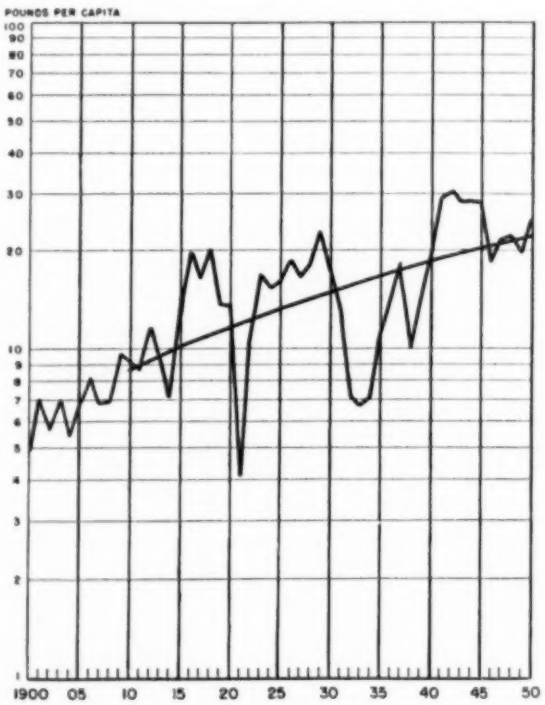


Fig. 6—Lines show estimated consumption per capita for electrical energy between 1900 and 1950. Power requirements for aluminum production are a vital factor in growth of the industry and in estimating stockpile needs.

to be presumed that the salvage value of the aluminum can would not be overlooked as a source of revenue. If future aluminum can makers are able to capture only a modest percentage of the *tin* can market, some very fancy demand figures might appear on the horizon.

The building industry—The building industry may easily be the largest single market for aluminum. The use of aluminum siding and roofing is established in numerous fields, especially in farm and poultry buildings where the heat-reflecting qualities of aluminum make significant contributions to the health of animals and fowl and consequent production. Because of these same qualities and because of the saving in maintenance through lack of corrosion and the necessity for painting, aluminum is gaining a wide interest in the building fields for all types of structures. Aluminum screens and windows are thoroughly established. A new office building of radical design has been erected in Pittsburgh, using aluminum in place of masonry, as well as in the heating and cooling system. One of the major producers estimates the use of aluminum in construction at 1.5 million tons within five years.

The electrical industry—The electrical industry is using extensive quantities of aluminum. Because of the lighter weight (on a conductivity basis 1 lb of aluminum replaces 2 lb of copper) aluminum is preferred material in most high tension transmission lines. It is rapidly finding acceptance as a substitute for copper in covered wire, in bus bar and more recently, in the smaller sizes of wire such as communication wire and motor windings, transformer windings, etc. Some of the larger companies are actively experimenting with aluminum in this field.

Irrigation piping—There seems to be a growing conviction that use of irrigation water through a sprinkler system as contrasted with ditching, represents an almost revolutionary change in irrigation practice, bringing with it substantial improvements in the yields of a wide variety of crops. In addition, sprinkler irrigation can be employed in many cases where ditch irrigation is impossible. This system involves pumping and piping water from available sources, including main irrigation canals, over the fields and, through distribution lines, into sprinkler systems. In most cases the lines are movable and thus, the system is most flexible. The lightness of aluminum recommends it highly for this purpose. This use is rather severely restricted at present, but predictions are freely made that when aluminum tubing is more readily available, the practice will spread extensively, both here and abroad. There are some 460 million acres of good cropland in the U. S. with 350 million under cultivation. Yields from a good part of the latter acreage could be considerably improved with more adequate irrigation. The use of aluminum piping and sprinklers, the merit of which has been amply demonstrated, would create a market of about 50 lb of aluminum per acre in this industry, a demand which might well run into fantastic figures.

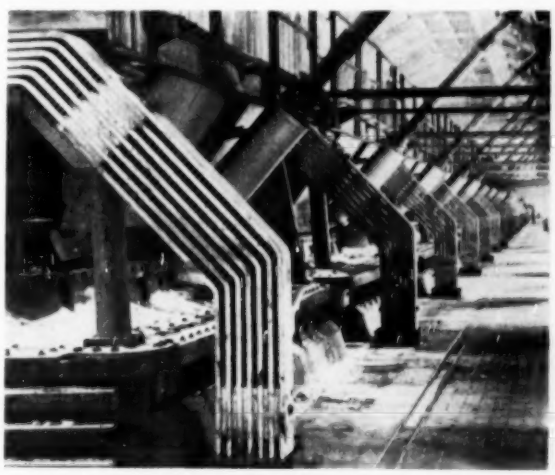
Substitutes for Aluminum

As against these favorable influences, aluminum is not invulnerable to replacement by other materials. The rapid advances in the plastics industry, especially in the combinations of plastics and fibreglass, are beginning to produce materials with the characteristics and perhaps economic advantages which may cause them to be preferred in a wide variety of uses. It is difficult to evaluate this factor, but it might be considerable. The plastics industry is a dynamic one in which a large number of able research people are constantly developing new products. The same may be said of the steel industry. Alloy steel has indeed been a competitor of aluminum for a long time. For the moment, aluminum appears to have nosed out its rival in a number of fields, such as truck trailers, but this may not necessarily be a permanent trend. Much research work is now under way in an effort to develop lighter steel alloys with characteristics that might easily compete with aluminum. Magnesium is a much younger metal than aluminum. Being even lighter, magnesium can certainly look forward to a healthy future in which aluminum may indeed lose out in some areas. The relative cost of production of the two metals will be a factor, but weight for weight, they are quite close at present. Widespread replacement of aluminum by magnesium will be dependent, of course, upon development of a larger fabricating system than the present one. With the resourcefulness of American businessmen at its service, the future of magnesium certainly should not be discounted. It is already a fairly strong competitor for lightness in the automobile field. Titanium is certainly a potential competitor in the future, if and when its cost declines.

Before leaving the subject of future civilian demands for aluminum, one should consider the price structure. Aluminum is the only metal in wide use, with price about the same as before World War II. On a volume basis, that is to say for an equal number of cubic inches, it is by far the cheapest of the major metals except for the approximately equal position of magnesium.

Stockpiling for Security

In its broadest sense stockpiling policy should be directed to the accumulation of enough critical material to protect the nation from the terrific surge of demand for military and essential civilian purposes during a war or emergency. Because of its importance in aircraft and other air-borne equipment, aluminum is particularly subject to these giant surges. The effect of the absence of a stockpile is well-known. It means that in an emergency or war



Alumina is reduced to make aluminum with the help of these electrolytic cells at Alcoa's Point Comfort, Texas works.

Aluminum appears to have a wide future application in irrigation. Here Reynolds Metals Co.'s Kingsiphon handles huge volumes of water. The siphon is capable of delivering 320 gal per min, making it suitable for ditch and flood type irrigation.

period the nation must hectically construct, under the most unfavorable conditions, expensive plants, using scarce material and manpower resources at exactly the wrong time and, concurrently, largely depriving the country, by strict allocation, of a widely used material. Aluminum crises also cause difficulty because of the impinging of a new expansion program on either existing, or future power resources which will be in great demand for other purposes. This tragic impact can be greatly lessened, if not eliminated, by the possession of a large stockpile of aluminum metal. The stockpile is a national military stockpile and should never be used for market regulatory purposes, or for other reasons not connected with a military or defense program. This point cannot be over-emphasized.

It is no secret that successful stockpiling of a material is exceedingly difficult during times when an active demand for the material in question is asserted by the business community. Successful stockpiling should, therefore, have as a base a genuine, if temporary, surplus of capacity. From Fig. 1 it will be noted that if estimates are correct for future requirements at the rate of 5 pct per annum per capita for the civilian economy, there will be an opportunity to stockpile a very considerable amount of aluminum over the next few years. If the demand develops at a more rapid rate than anticipated, this opportunity will not last long.

The Government, through its so-called supply contracts with most of the primary producers who have undertaken to expand facilities, is committed to purchase up to 100 pct of the output of these facilities for about five years following their completion, if the producers cannot dispose of the metal to customers. In addition, the Government has the actual option to purchase up to 100 pct of the metal if it chooses. In other words, there is both a *put* and a *call* provision for an aggregate theoretical amount of well over 3 million tons of aluminum, running on a decreasing aggregate scale into the year 1959. Needless to say, it is not expected either by the producers or by Government that the entire output of the new facilities will be required by or *put* to the Government. What it really means is the primary aluminum system will run at full capacity almost for the remainder of this decade, the Government acquiring under its contracts either by *put* or *call* a minimum amount consisting of whatever surplus not required by the civilian economy and the defense program. On the estimate of an average increase in the consumption rate of the civilian economy of 5 pct per annum per capita, assuming no war or change in the military program, this would mean that the government will acquire approximately 2 million tons of metal by 1959.

Although they cannot be presented because of high classifications, there now is quite a good estimate of the requirements for aluminum for a five year war. *Quite a good estimate* is used advisedly. No estimate of requirements for such basic materials as aluminum or copper is likely to be very accurate prior to the commencement of a war. Nevertheless, a careful job has been done of screening and time-phasing and correlating war requirements in relation to such scarce materials as nickel and such potential limiting factors as the labor force in the chew-up industries. These war requirements are very large and reach a peak late in the second or early in the third year of the assumed war. It was because of the magnitude of these requirements that the Government, last fall authorized a further expansion in aluminum production of 200,000 tons. This step was an attempt to cut to feasible size the problem arising in case of war in the reasonably near future. If stockpiling can be carried out along the lines suggested, the size of the task faced if war should start, would be progressively reduced as time passes. Indeed, if there is a further three years of peace, the U. S. would have a stockpile big enough to protect it against the necessity of adding anything to the primary aluminum system after *M* Day. The stockpile at that time would be performing exactly the function for which it is specifically designed—to protect the country against a sudden terrific surge and to eliminate the impact of building a new aluminum system on the economy. If no war comes during the rest of this decade, the Government will have acquired, under its supply contracts, a stockpile sufficiently large so that there will never be another aluminum crisis or another aluminum *czar*. Such a stockpile might even make it possible, in case of a severe power shortage after an attack, to shut down aluminum plants and divert power to a higher priority use, such as atomic energy. A stockpile of 3 million tons of aluminum would, in effect, represent a stockpile of approximately 60 billion kw-hr, or about one eighth of the expected generation of electricity in 1954.

A good many times in the last decade or so there has been the cry of *too little too late*. Americans can rejoice in the fact that in most cases the *too little* finally became enough and the *too late* turned cut to be soon enough for final victory. Nevertheless, there were times during the war and indeed there are times now when all wished and continue to wish for *more sooner*. In the case of aluminum, the U. S. probably has open to it, assuming no war in the near future, the ability to acquire *enough and on time* if the country is prepared to plan it that way. Within the framework of the nation's needs for defense and on the theory that this may not be the last crisis facing it, the price of a large stockpile and of a generous supply of aluminum seems small indeed for the advantages which it will bring.

Sponge Iron Used As a Precipitant for Copper

SPONGE iron as produced at Anaconda is a fine, −35 mesh impure product, about 50 pct metallic iron, obtained from reduction of iron calcine at a temperature of 1850°F using coke resulting from slack coal. Investigation of the treatment of Greater Butte Product, Kelley, ore at Anaconda early showed the desirability of using sponge iron as a precipitant for the copper in solution resulting from desliming of the ore in a dilute sulphuric acid solution.

Anaconda had done considerable work on the production of sponge iron in 1914 for use as a precipitant of copper from leach solutions. Some success and considerable experience were attained at the time. They were indicative that sponge iron might be successfully made by a modification of the process used in 1914, a batch process in which an iron calcine was reduced by means of soft coke, resulting from noncoking coal, in a Bruckner-type revolving horizontal cylindrical furnace widely used 50 years ago.

It was thought that the process, if changed to a continuous one, might work out satisfactorily. These favorable conditions at Anaconda justified the investigation: 1—Sufficient tonnage of good grade iron calcine resulting from the roasting of a pyrite concentrate in one of the acid plants, at substantially no cost. 2—Reasonably cheap natural gas. 3—No need for production of a high grade product. 4—No need for obtaining a consistently high reduction of the iron in calcine.

A small revolving Bruckner-type furnace about 2 ft ID x 4 ft long set up for early pilot work showed that a satisfactory product could be obtained at reasonable cost. It also indicated a marked advantage in preceding the reduction furnace with a furnace of similar size and capacity for preheating and roasting out any residual sulphur from the feed. The small furnace was operated for several months, various details of the process were worked out, and sponge iron was produced to supply a pilot LPF plant which treated 300 lb of Kelley ore per hr. Later a second pilot furnace 5 ft in diam and 12 ft long inside confirmed the data of the small furnace and gave a basis for design of the final plant.

At Anaconda a pyrite concentrate, running about 48 pct S, is recovered from copper concentrator tailings by flotation. This concentrate is roasted to sulphur of 3 pct or less at the Chamber acid plant. The iron calcine containing about 57 pct Fe and 18 pct insoluble is reroasted and preheated in a reroast furnace preceding the reduction furnace. Both are of the Bruckner type. The reroasted calcine is fed into the reduction furnace at 800° to 1000°F along with 30 pct slack coal. In the feed end of the furnace the volatile is burned from the slack, giving a soft coke which readily serves for iron reduction. Hard metallurgical coke will not serve the purpose, since it does not reduce CO_2 readily at a temperature of 1850°F. All indications are that the actual iron reduction is accomplished by carbon monoxide below the bed surface, which is 30 in. deep at center.

Table I. Production of Sponge Iron at Anaconda Copper Mining Co.

Daily Operating Data

Calcine feed, tons	65	Slack coal, tons	20
Final product, tons	45	Return coke, tons	5
Gas	300		
Iron reduced, pct	72		
Bed temperature, °F	1850		

Analyses

	Total Fe, Pct	Metallic Fe, Pct	S, Pct	Insoluble, Pct
Feed	58		0.50*	18
Final product	70	50	0.8	24

* Reroast to reduction furnace.

Apparently there is a constant interchange:

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2. \quad CO_2 + C = 2CO$$

Actually iron oxide is reduced by CO at somewhat lower temperature than the 1850°F used in the process, but this temperature is necessary for a satisfactory furnace production rate. Gas flames from four 3-in. Denver Fire Clay Inspirator burners are played directly on the bed, which is slowly cascaded by the 1 rpm of the furnace. An excess of coke is necessary to assure maintenance of good reducing conditions in the furnace bed.

A satisfactory final sponge iron product involves two steps, production of the iron, and prevention of reoxidation during cooling. The firing end of the furnace is almost entirely enclosed and the product overflows at the firing end into a receiving duct in which raw gas is passed to maintain a reducing atmosphere. The furnace product passes from the duct directly into a Baker cooler where it is cooled from about 1500°F down to about 150°F. The Baker cooler has rotary seals at both ends to exclude air and prevent reoxidation of the sponge iron.

For satisfactory production of sponge iron sulphur content of the feed to the reduction furnace should not exceed 1 pct. A larger amount gives wall accretions, ball formation in the bed, and a dark inferior product that gives a poor efficiency in precipitation of copper.

Both pilot plants indicated the need for a boring bar in a commercial plant. At the 1850°F temperature necessary for satisfactory production from an individual furnace, there is a tendency for the formation of accretions on the walls of the furnace, and it is not feasible to remove these accretions by hand barring. A mechanically operated water cooled boring bar was designed which enables removal of the accretions satisfactorily.

The cooled furnace product requires preparation for use, principally reduction in size to −35 mesh and recovery of excess coke for return to the reduction process. Size reduction is desirable to lower the tendency of sponge iron to sand out in the flotation cells of the LPF plant.

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Silicon Content of Blast Furnace Iron Lowered by Oxygen Injection in Ladle

by P. S. Leroy

ALTHOUGH the practice of oxygen injection into liquid steel in the open hearth or electric furnace for efficient removal of carbon from the bath is well established, injection of oxygen into hot metal in the ladle for desiliconization is not common.[1] Low silicon iron is beneficial for the basic open hearth, and is even more necessary for basic Bessemer converter practice.

The French Iron & Steel Research Institute (Institut de Recherche de la Siderurgie at St. Germain, near Paris) has done considerable work pertaining to oxygen injection into hot metal in a ladle for subsequent charging into basic converters. The entire hot metal production of a French steel plant, 900 metric tons of iron per day, is now being treated with one of the methods evolved whenever silicon content is above 0.50 pct. In this discussion, the desiliconizing treatment will be called *prerefining*.

Sound basic bessemer converter practice requires an iron with a silicon content below 0.50 pct for satisfactory blowing. This limit is lowered to 0.40 pct if oxygen enriched air is used.[2] Tests to lower the silicon content of hot metal before charging it into the refining furnaces had the following objectives:

1—Lower the silicon content of hot metal by treating it in the ladle whenever it was over 0.50 pct on tapping from the blast furnace.

2—Obtain hot iron with a silicon content consistently lower than 0.40 pct, so it can be blown in the converter with oxygen-enriched blast.

3—Lower a 0.70 pct silicon acid blast furnace iron $\left(\frac{CaO}{SiO_2} = 1\right)$ to less than 0.50 pct.

4—Lower the silicon content of hot metal to any desired level.[3]

Oxygen for Carbon Reduction

For the open hearth and the electric arc furnace, the simplest method is to immerse oxygen lances, often coated with a high temperature refractory to minimize lance burn-off, into the bath at an angle. Oxygen pressure used is comparatively low, usually 70 to 100 psi. Too high a pressure would cause *slopping*. At the immersion angle the tip of the lance seems to be at a vertical depth of 6 in. to a foot below the slag surface.

Another method, described by Reinhardt,[4] consists of blowing with higher oxygen pressure, 140 to 160 psi, employing a water-cooled lance with a copper head provided with a nozzle a few inches above the slag surface. The oxygen stream, at an angle 30° to vertical, is able to penetrate through the slag, because of its high speed. Advantage of this method is that the lance assembly, not being immersed, will not burn off.

Choice between these two methods depends only on local conditions, since results obtained with an oxygen flow of about 500 cfm are about the same in both instances.[5]

The oxygen injection efficiency varies widely with the carbon content of steel treated. Hughes and Norris[6] have established that the volume of oxygen injected per ton of metal per point of carbon removed is 1 to 2 cu ft for 0.90 to 1.00 pct carbon, and increased to 40 to 60 cu ft for carbon contents below 0.05 pct. Assuming that 3.15 cu ft of oxygen are required to burn 0.01 pct of carbon in a metric ton of iron, and assuming the reaction product is entirely CO, the efficiency of the injected oxygen would range from 5 to 8 pct for carbon contents below 0.05 pct, all the way to 157 to 315 pct for carbon contents of 0.90 to 1.00 pct.

The efficiencies above 100 pct prove that the oxygen gas, besides being chemically active, creates a physical agitation which results in intimate contact of the slag and furnace atmosphere with the metallic bath, increasing the rate of oxidation.

Decarburizing vs Desiliconizing

It is believed the fundamental difference between oxygen injection into a furnace to decarbonize a metal during the refining period, and the oxygen lance practice applied to iron in a ladle to remove part of the silicon, is as follows:

1—In decarbonizing molten steel in a furnace, the oxygen injection is carried out under an active slag. The metallic bath is shallow and has a wide surface area in contact with an oxidizing atmosphere. The main reaction product is carbon monoxide gas bubbles which create a vigorous boiling action.

2—In desiliconizing iron in a ladle, the slag formed is relatively inert. The prerefining slag is very foamy and has, during oxygen injection, an apparent volume 2.5 times its real volume. Perhaps it is one of the reasons why that slag is chemically inert towards liquid iron, in spite of its high content in iron oxides. With a lime addition, the slag is no longer foamy and the oxygen efficiency increases. The surface area of the bath is small compared to its depth. No vigorous boiling action takes place, because the reaction product is mainly the oxides of silicon, manganese, and iron which enter the slag. Thus, the transfer of oxygen from the atmosphere to the bath is very small compared to decarburizing molten steel.

It is therefore not surprising that oxygen efficiencies are low and far from the values of 80 to 85 pct obtained in the open hearth, with carbon contents between 0.40 and 0.10 pct.

Oxygen for decarbonizing, is the most extensively used in the open hearth in carbon ranges below 0.40 pct. It is believed that in the higher carbon ranges, notwithstanding a better oxygen efficiency, the iron oxide fumes and slag projections are abundant enough to deteriorate the furnace roof. Moreover, for carbon

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contents below 0.40 pct, it is not so much oxygen efficiency that counts as saving in furnace time. Likewise, lowering silicon content of iron is of sufficient interest to justify a lower oxygen efficiency than that obtained in decarburizing in an open hearth furnace. Nevertheless, it was necessary to develop operating techniques to obtain optimum oxygen efficiency in desiliconizing iron in the ladle, efficiency being defined as:

$$\frac{\text{oxygen in } SiO_2 \text{ produced}}{\text{oxygen supplied}} \times 100.$$

Desiliconizing at Blast Furnace Runner

All trials of oxygen injection in the iron flowing in the blast furnace runner have failed. The chemical effect is practically nil. With the immersed lance process, increase of the blowing pressure caused excessive *slopping* before favorable conditions for the reactions between gas and liquid metal could be established.

Using a copper lance with its tip a few inches above the iron stream, it was possible to reach the bottom of the runner with a moderate pressure, 40 to 50 psi. However, contact between iron and oxygen remained insufficient, because the iron stream diverged from the oxygen jet and drifted towards the banks of the runner, like the water of a stream into which a stick is plunged.

Oxygen Injection in Transfer Ladles

The transfer ladles employed in the experiments were of 30-metric ton capacity. Four series of tests were made, each employing a different technique.

Oxygen Injection at the Slag-Metal Interface with Inclined Lances: Two steel lances, ¾ in. ID, at an angle of about 25° to the horizontal, were immersed into the iron. This technique is shown schematically in Fig. 1.

With an operating pressure of 40 to 50 psi, a flow of 140 to 160 cfm was obtained through each lance. This flow did not agitate the metal bath to any great extent.

At the commencement of oxygen injection, the bare lances were consumed at a very high rate, 18 in. per 100 cu ft of oxygen injected. When sufficient prerefining slag was formed, it froze onto and coated the lances to minimize the burn-off rate. With refractory coated lances, the high rate of burn-off at the start of lancing was reduced.

During lancing, the steel pipes exerted a considerable back pressure when feeding more lance into the metal. This was true even when held steady. Inserting the lance further into the metal did not result in the lance penetrating further into the bath. Either the lance quickly burns back close to the slag-metal interface, or if the lance does not burn off, the combined effect of softening of the lance, because of heat and the bucyant effect of the hollow portion, is sufficient to bend the lance so its outlet is back at the slag-metal interface. Positive proof of this was furnished during a run in a ladle with a wornout lining. One of the lances penetrated through to the ladle wall, causing a break-out. It is therefore inferred that the lance, no matter how apparently deeply immersed, assumes a curvature that makes the point of injection very close to the slag-metal interface.

As a result, oxidation proceeds in the surface layers and, as reaction products (SiO_2-MnO-FeO) are not gaseous, the effect seems to be localized. The

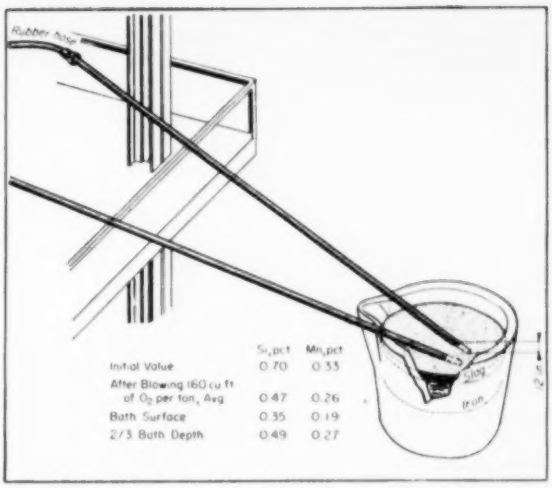

Fig. 1—This shows the apparatus for blowing at an angle of 65° on surface of metal after ladle filling. Oxygen pressure above rubber hose was 57 psi, and total oxygen flow was 321 cu ft.

vigorous reaction, as obtained on decarburizing in a furnace, is not present. Nevertheless, thermal and chemical diffusion takes place between surface and underlying layers.

Optical temperature measurements made on the iron stream when pouring the metal into the mixer after oxygen injection, immersion thermocouple measurements and iron samples taken at various intervals during pouring from the ladle, have shown that:

1—The thermal effect reaches the bottom of the ladle when injected oxygen volume is greater than 70 cu ft per ton of iron.

2—Oxygen efficiency is maintained at the 40 pct level up to 180 cu ft of oxygen injected per ton of iron, and then decreases steadily. This results from exhaustion of silicon on surface layers and insufficient replacement of silicon from deep layers by diffusion and convection. Above 180 cu ft, the amount of injected oxygen which combines with Fe, steadily increases. With the above procedure, oxygen volumes injected vary from 140 to 180 cu ft per metric ton of iron, or 160 cu ft as the standard injection volume. Of course, the limiting value of 180 cu ft applies only to a 0.70 pct silicon iron, and increases with the silicon content.

3—With an oxygen volume of 160 cu ft per ton of iron, the silicon content is lowered from 0.70 pct to an average of 0.47 to 0.48 pct, and the Mn content from 0.33 pct to a mean value of 0.25 to 0.26 pct. Therefore, the amount of silicon oxidized is about 3 times that of manganese although the initial silicon content is only 2 times the initial manganese content. Phosphorus and carbon are not oxidized.

The amount of Fe oxidized during the operation is rather high. It is lost either in the slag or abundantly evolved as red fumes. A little over 1 pct by weight of iron treated is lost.

The temperature increase reaches an average of 90°C (160°F). The heat balance of the operation shows that the amount of heat generated by Fe oxidation was almost equivalent to that produced by silicon oxidation. As a result, various procedures were tried to improve the operating technique so oxygen may react at a greater depth into the metal.

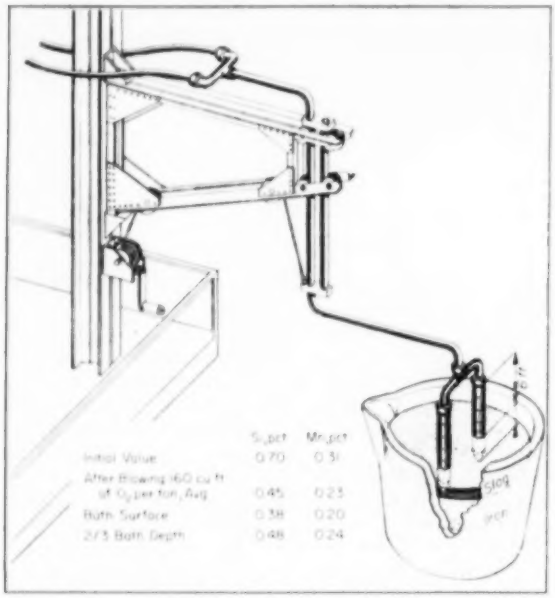

Fig. 2—In this vertical injection method, two steel lances coated with a fireclay slurry were used. Oxygen pressure above rubber hose was 43 psi, and total oxygen flow was 339 cu ft. Maximum practicable immersion depth was about 12 in. Above this value lance vibration and slopping became excessive. Immersion depth during injection averaged 4 in.

Vertical Blowing with Lances Immersed in a Full Ladle of Iron: Fig. 2 shows the operating device schematically. Both steel lances, ¾ in. ID, were coated to a length of 7 ft with a refractory clay. Best results were obtained with a silicious-aluminous clay made up of a highly refractory cement with a calcium aluminate base. Lance burn-off was stabilized at about 1½ in. per 100 cu ft of oxygen when injection was made at the slag-metal interface, and about 1¾ in. per 100 cu ft when attempts were made to inject into the iron. The latter burn-off rate was lowered to 1½ in. per 100 cu ft of injected oxygen when a stainless steel pipe was used.

When the oxygen injection was located at the slag-metal interface, the two lances remained very still, almost without vibration. In the first operating procedure, the lances behaved similarly. When the lances were immersed into the hot iron, vibration began which increased with increasing immersion depth. Maximum depth of immersion was 16 in. At this penetration, slight in relation to the bath depth of about 6 ft, the lance vibrations were violent, causing iron and slag to *slop* although the rim of the ladle was 1 ft above slag level.

It was necessary therefore to limit the injection depth to a maximum of 10 in. Pressure, being limited to 42 psi, the lance was immersed until moderate vibrations were obtained. As the pipe burned off, vibrations decreased. When the latter were about to cease, the lances were again plunged a depth of 6 to 10 in.

In spite of these precautions, the agitation of the bath was much more violent than in the first operating procedure which resulted in slag and iron being ejected from the ladle, and in a more moderate temperature increase. Thermal effect reaches to the bottom of the ladle at an injected oxygen flow of 50 cu ft per metric ton of iron.

Oxygen efficiency is maintained at 44 pct with oxygen flows up to 180 cu ft per ton of iron, then decreases. For an injected volume of 160 cu ft, the silicon content of the iron decreases from 0.70 pct to an average of 0.45 pct, while the manganese content decreases from 0.31 to 0.23 pct. The ratio $\frac{\text{oxidized Si}}{\text{oxidized Mn}}$ is still about 3.

The amount of Fe oxidized during the operation was similar to that of the first operating procedure, i.e. more than 1 pct of the iron treated. Temperature increase was on an average of 58°C (105°F), instead of 90°C (162°F) with the first procedure.

Thus, this second procedure is only slightly better than the preceding one, and variations of iron analysis and temperature differences between surface and bottom layers remain high.

Vertical Blowing by Means of Immersed Lances During Ladle Filling at the Blast Furnace: With the preceding injecting device, it was necessary to inject at the slag-metal interface to avoid vibrations. The same device was used during ladle filling at the blast furnace, as shown in Fig. 3. The mixing action of the iron stream caused a continuous burn-off of the lances, so that the injection point was always close to the slag-metal interface. It was therefore not necessary to withdraw the lances to avoid vibrations as the ladle fills. Time of ladle filling was generally between one half and two thirds of overall blowing time, blowing being completed on the bath surface after the end of filling. Rate of lance burn-off depended mainly on the speed of ladle filling; on the average, it was 1½ in. per 100 cu ft of injected oxygen. With a small addition of lime to the ladle, it was possible to reduce the burn-off to less than

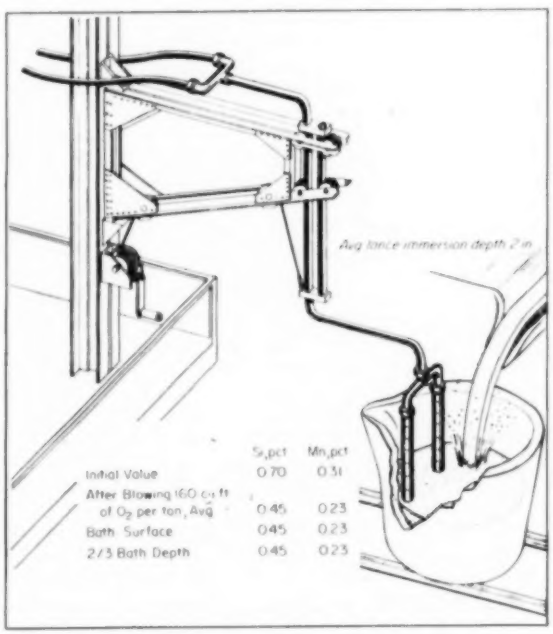

Fig. 3—In this method of vertical injection during ladle filling, two steel lances coated with a fireclay slurry were used. Oxygen pressure above rubber hose was 43 psi, and total oxygen flow was 321 cu ft.

Table I. Results Obtained With Industrially Applicable Procedures for Desiliconizing. Initial Si Content of Iron, 0.70 Pct; Initial Mn Content of Iron, 0.31 Pct.

	Two Immersed Lances Blowing During Ladle Filling	One Nonimmersed Lance			
		Single Hole Nozzle	Multiple Hole Nozzle		
			Without Lime Addition		With Lime Addition
Blowing Pressure, Psi	30 to 70	170 to 210	170 to 210		170 to 210
Oxygen Injected, Cu Ft per Metric Ton Iron	160	90	160	215	160
Silicon Removal, Pct	0.25	0.19	0.24	0.31	0.30
Oxygen Efficiency, Pct	44	61	42	42	53
Manganese Removal, Pct	0.08		0.07		0.08
Ratio-Oxidized Si/Oxidized Mn	3.1	3.3	3.3	3.1	3.85
Iron Losses, Lb per Metric Ton Iron	18	9	11	17	7
Temperature Increase, °C	65	45	65	80	65

1 in. per 100 cu ft. With this procedure, spitting was greatly reduced.

The essential feature of this third procedure is the high homogeneity of iron obtained. Oxygen efficiency was not improved in spite of the mixing action of the iron, because oxygen losses to the atmosphere were higher than with the two other procedures.

Nevertheless, in spite of the similar oxygen efficiency, as compared to the first and second procedures, this injection method, during ladle filling, is worthwhile, because it does not slow down ladle shuttle between blast furnace and mixer, and furnishes a very homogeneous iron. Thermal effect reaches to the bottom of the ladle, regardless of oxygen volume injected, since injection process begins when the bath is only 16 in. deep. Results are given in Table I.

Advantages of this method over the preceding ones are: 1—Lance introduction is much easier, and no positioning control is required during injection; 2—metal losses through spitting are almost negligible; 3—iron obtained is most homogeneous; 4—temperature increase, in comparison with a reference ladle, is 65°C (117°F); 5—Fe losses through slagging are markedly lower; and 6—there is almost no slowing down of the ladles shuttle between blast furnace and mixer.

However, oxygen efficiency, for an initial silicon content of 0.70 pct, is still only 44 pct up to an oxygen volume of 180 cu ft and decreases above this oxygen value.

Vertical Blowing with High Pressure Oxygen: The three preceding operating methods were more or less similar to the immersed oxygen lance practice used at the open hearth. This fourth procedure is based on the same principle followed by A. E. Reinhardt,[4] i.e. use of a high-pressure gaseous jet of great penetrating power through a nonimmersed lance.

Water-cooling of the lance was not necessary. Thermal conditions, in this case, were much less severe than in the open hearth and the lance was protected only with a thin refractory coating.

The first lance used had only one orifice and was vertically positioned at a distance of about 2 in. from the slag surface; oxygen was injected at a pressure of 170 psi. Results obtained are given in Table I.

Up to 90 cu ft of oxygen per metric ton of iron, oxygen efficiency, for an iron with 0.70 pct initial silicon content, is above 60 pct, and silicon removal was 0.19 pct. Above 90 cu ft, oxygen efficiency decreased steadily. At 160 cu ft, efficiency was down to 40 pct, and amount of silicon removed was only 0.23 pct. This drop in oxygen efficiency was caused by the building up of a kind of stalactite at the end of the lance, formed by solidification of drops of liquid slag flowing along the outside wall of the lance. Its formation was not instantaneous. The stalactite took up queer forms, disturbing the oxygen flow, but started to become a hindrance only after 100 cu ft of oxygen per ton had been injected.

Therefore, it could be considered as established that this procedure was the most efficient one for the removal of 0.20 pct silicon from a 0.70 pct silicon iron. To increase the amount of silicon removed, preserving at the same time a satisfying efficiency, it was necessary to prevent the formation of the stalactite.

To minimize the amount of liquid slag splashed onto the lance, it was logical to attempt to blow at an angle instead of vertically.

A first trial was made at an angle of 25° to the vertical. From the chemical standpoint, the effect was almost nil. Oxygen efficiency was below 10 pct, red fumes were almost nonexistent. A kind of *total reflection* of the oxygen jet on the iron surface occurred at that angle. This again emphasized the difference between carbon reduction in the open hearth bath which, boiling by itself, can take an oxygen jet at an angle of 30° to the vertical.[4]

On iron, the 25° blowing angle gave the stalactite a dissymetrical form which did not disturb the flow of oxygen in the least. The angle of blowing was then reduced to 9° to the vertical. Up to 90 cu ft per ton, oxygen efficiency was slightly better than in the preceding case, but the stalactite formed almost as quickly as with vertical blowing.

To prevent the liquid slag flowing towards the oxygen jet, the main injecting orifice was surrounded with a crown of vertical channels of small diameter. This caused the slag to freeze around the auxiliary blowing crown, thus leaving the main jet undisturbed. The chemical efficiency of the side jets was lowered by the stalactite which, in return, lowers the overall oxygen efficiency. The latter can be improved by increasing the ratio of oxygen flow of the main jet/oxygen flow of the auxiliary jets.

Investigations to find out the optimum ratio are not yet completed. Table I presents the results obtained with the first type of nozzle tried, i.e. without the auxiliary jets, under a blowing pressure of 170 to 210 psi. Thermal effect reaches the bottom of the ladle from a flow of 50 cu ft of oxygen per ton of iron.

Oxygen efficiency at 42 pct is not very high, but remains at this level above 180 cu ft of oxygen per ton, up to 250 cu ft of oxygen, which is, for the time

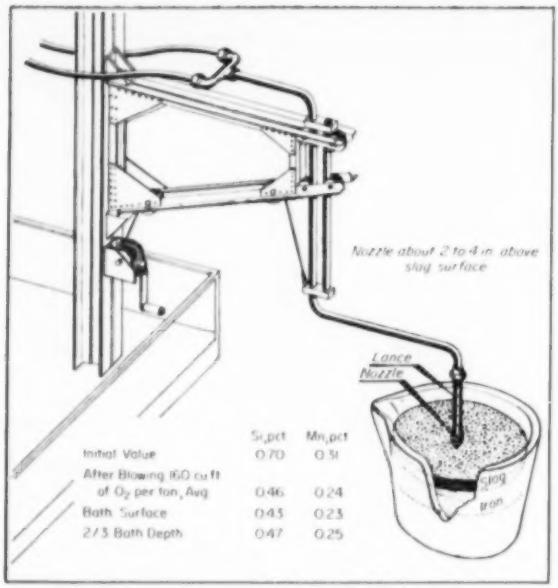

Fig. 4—One copper lance is used in this method of high pressure vertical blowing. Oxygen pressure was 170 to 210 psi, and oxygen flow was 357 cu ft.

being, the limit of tests on irons with 0.70 pct initial silicon content. Investigations will be carried out in the near future, with oxygen volumes greater than 250 cu ft. The 42 pct oxygen efficiency insures a silicon removal of only 0.24 pct for an oxygen flow of 160 cu ft per ton, but it allows a silicon removal of more than 0.30 pct from an oxygen flow of 195 cu ft per ton.

Operating on a 1 pct silicon iron instead of 0.70 pct, the average decrease in silicon content may reach 0.31 pct (instead of 0.24 pct), i.e. an oxygen efficiency of 54 pct (instead of 42 pct). The amount of Fe oxidized in the process is about 11 lb per ton of iron. This shows a marked decrease relative to the preceding procedures.

Advantages of high speed blowing into the iron can be summed up as:

1—With a one-orifice lance, it is possible to remove 0.20 pct silicon, maintaining at the same time an excellent oxygen efficiency.

2—Present design of multiple hole nozzle allows a silicon removal of over 0.30 pct from an iron with a 0.70 pct initial silicon content, but with a moderate oxygen efficiency which it is hoped will be improved in the near future.

3—The lance is not damaged in the process, and the procedure is very easily carried out.

4—Fe losses are low.

5—The treated iron is somewhat less homogeneous than with the third procedure, but distinctly better than that obtained with the first two procedures.

Addition of Lime During Ladle Filling: To increase the amount of oxygen fixed on silicon at the expense of that fixed on manganese and Fe, it was logical to add lime in the ladle. Experiments are only beginning with this new method, but it has already produced promising results.

About 15 lbs of low sulphur lime dust per ton of iron have been shovelled into the ladle during filling at the blast furnace or upon the iron stream flowing in the runner. When the ladle was full, oxygen blowing was applied, using the multiple hole nozzle lance employing an oxygen volume of 160 cu ft per ton. Results obtained are given in Table I. Operating on a 1 pct silicon iron, the average silicon removed was 0.37 pct, i.e. an oxygen efficiency of 65 pct, which is excellent. The amount of Fe oxidized during the process was about 7 lb per ton of iron, a minimum never attained before, corresponding to a maximum silicon removal.

Conclusions

The procedures that will be retained as fit for industrial applications are the third and fourth. They would then be completed with a device for the recovery of iron oxide dust contained in the fumes. The ladle would be, at least, partly covered during the operation, which would allow a further gain of temperature.

The temperature increase of the iron is most useful, especially in the basic Bessemer process. Moreover, it may eventually make up for heat losses produced by an intermediate desulphurizing operation between the blast furnace and the steel plant, obtained either by additions of sodium carbonate in the ladle, or by lime additions in a special furnace.[7]

Nevertheless, silicon removal remains the main objective. Results obtained to date can still be improved. Even with the present efficiency, oxygen injection into the iron is commercially feasible and practicable.

From December 1952 on, the fourth procedure will be used to treat the whole hot metal production of a French steel plant, whenever the silicon content is above 0.50 pct.

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Rimming Steel Production Rate Studied by Multiple Correlation

by W. W. Black and C. R. Taylor

SHORTLY after the installation of two 70-ton electric furnaces at Middletown, it was decided to undertake a study of the factors affecting production rate on these furnaces. It was particularly desired to obtain information about the effect of the use of oxygen, particularly to melt down scrap. A small amount of oxygen was used to eliminate carbon. No effort was made to keep this oxygen separate from that used to burn down scrap, but it was not more than 5 pct of the total amount used.

Data were collected on 100 heats of open hearth grades made in one of the electric furnaces. Since most of the heats made on this furnace were triple charge, those with four charges and two charges were excluded and only triple charge heats were studied. The method used for studying these heats was multiple graphical curvilinear correlation.

Tons per hour were tap to tap. Average megawatts were obtained by measuring the area under the curve on the recording megawatt meter for each charge with a planimeter and dividing by time. This gave a measure of the rate of heat input into the furnace by the arc.

Discussion of the results can best be made by discussing each curve separately. Many of the times included in this study turned out to be important. This is, of course, to be expected. Using the average tons per hour and the average size of the heat, the effects of 7 min time on the tons per hour of the heat can be determined. The curve of time vs tons per hour obtained in this way then can be compared to the actual times on the furnace.

Fig. 1 shows the effect of tap to start charge on tons per hour. This is the time from tapping the previous heat until the heat under discussion is started charging. The curve in this figure is considerably steeper than time alone and emphasizes the importance of minimizing this particular time to avoid the loss of high temperature furnace heat. Fig. 2 shows the effect of time of first charge in minutes vs tons per hour. Many of the charge variables, such as per cent silicon scrap from mixed steel, pig iron, thin bar, did not show any effect on tons per hour. It is probable that these variables affected charging time only; therefore, when the charging time was corrected for, these variables lost their apparent effect. Practically, however, it is apparent that the important way to change charging time is to increase the massiveness of the scrap going into the furnace, i.e., the weight per pan. The only exception to this effect was as shown in Fig. 3—the effect of pct bundles charged vs tons per hour. The effect, however, is weak. But it does indicate that bundles are harder to melt than most other types of scrap. Time of the second charge should be held at a minimum as shown in Fig. 4.

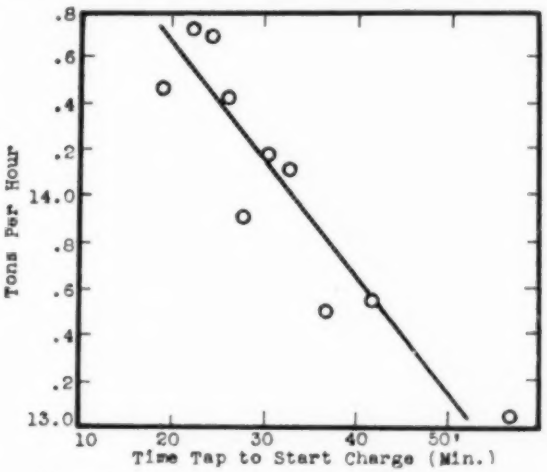

Fig. 1—The steepness of the curve emphasizes the importance of minimizing the time from tapping the previous heat until the heat under discussion is started charging to avoid loss of high temperature furnace heat.

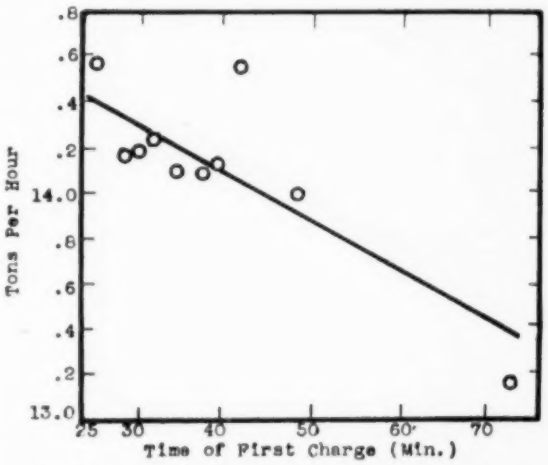

Fig. 2—Many charge variables affected charging time along and had no effect on tons per hour. The important way to decrease charging time is to increase the massiveness of scrap going into the furnace.

Time of the third charge, Fig. 5, also shows a trend steeper than time alone, again indicating the loss of high temperature heat during the charging period.

Figs. 6 and 7 show the effect of power input on the melting of the charge. The range covered on input was not very great since most heats were operated at or near maximum transformer capacity. Since these curves do not show any improvement in

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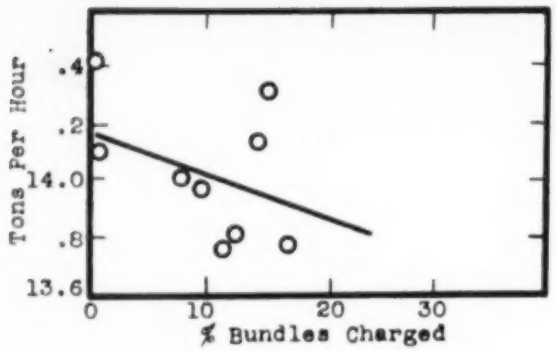

Fig. 3—Bundles are harder to melt than most other types of scrap, although the effect on tons per hour is weak.

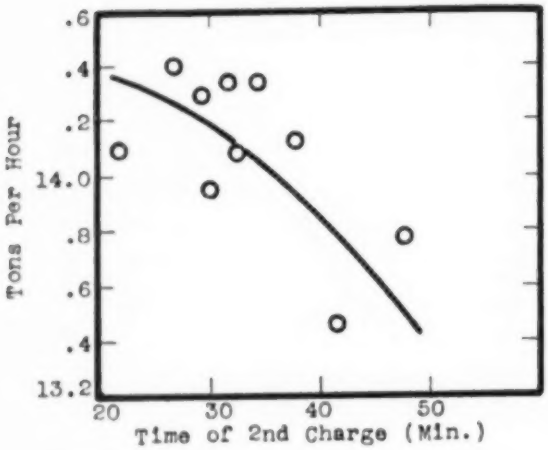

Fig. 4—The steep curve shows that time of the second charge should be kept at a minimum.

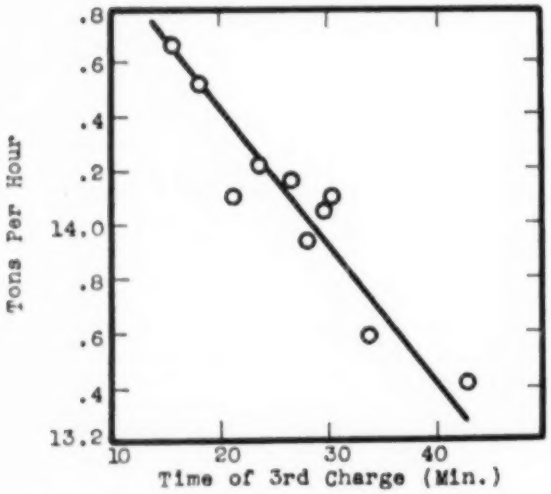

Fig. 5—Time of the third charge shows a trend steeper than time alone, and indicates loss of high temperature heat during charging period.

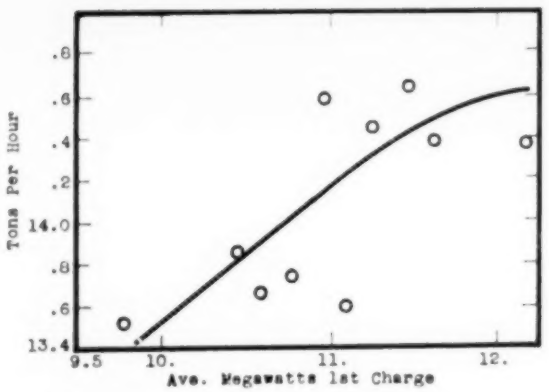

Fig. 6—No improvement in tons per hour was evidenced above 12 megawatts on the first charge and it is possible that this power level may be the maximum output of the 15,000 kva transformers.

tons per hour above 12 megawatts, it is possible that this power level may be the maximum output of the 15,000 kva transformers. This effect is in line with that reported by Stansel.[1]

Strangely enough, oxygen used on the first charge showed no effect on tons per hour. This may have been because it was used too early before the charge was preheated enough to burn readily. That used on the second charge, as shown in Fig. 8, shows some effect. That used on the third charge, as shown in Fig. 9, shows a greater effect. Fig. 10 shows the effect of time under cover to tap on tons per hour. It emphasizes the importance of melt-carbon control on electric furnaces. The total burned lime in per cent used on the heat has a marked effect on tons per hour as shown in Fig. 11. Limitations as to quality of scrap have a major effect of controlling this variable, but the amount of burned lime should be held to an absolute minimum.

Fig. 12 shows the effect of melt delays on tons per hour. These melt delays were, for the most part, power demand delays on the furnace.

There was some question as to whether these furnaces were being overcharged so total tons was included as a variable. It was indicated quite definitely that the furnaces were not being overcharged, although an average of 105 tons was being charged on a 70-ton furnace.

The number of buggies per charge did not show an effect on tons per hour. The effect of this variable

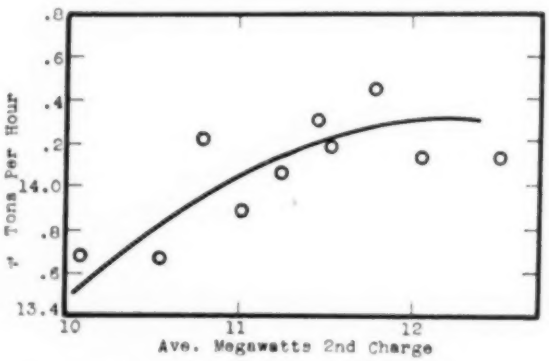

Fig. 7—For the second charge, as in the first charge, no improvement in tons per hour was noted above 12 megawatts.

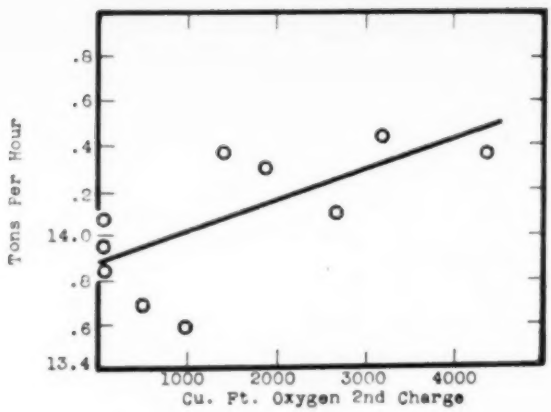

Fig. 8—There was no effect of oxygen used on the first charge on tons per hour, although some effect can be seen in this curve for the second charge.

appears to have been corrected by the use of charging time curves. The megawatts of power used to melt the third charge is another variable which did not affect the production rate. This can probably be accounted for by the small weight of the third charge which was usually only about 16 pct of the total.

Conclusions

Oxygen should be used to help melt the scrap on the second and third charges only.

Lime additions should be made so that efficient sulphur removal can be obtained with a minimum per cent of lime.

All charging times should be kept as low as possible, in particular, the time of the third charge should be held to a minimum.

Delays involving the loss of high temperature heat should be minimized.

Tons tapped should be held as high as possible.

Per cent bundles should be held to a minimum.

Average megawatts should be held as closely as possible to 12 during the melting period and not exceeded since higher megawatts than this will not increase the production rate and will increase the kilowatts used per ton.

[1] N. R. Stansel: *Trans.* Electric Furnace Conference, 1, 30 (1943).

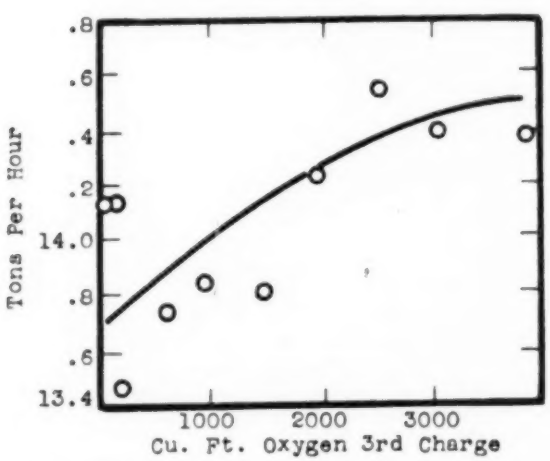

Fig. 9—Use of oxygen on the third charge shows a greater effect than was evidenced in the second charge, Fig. 8.

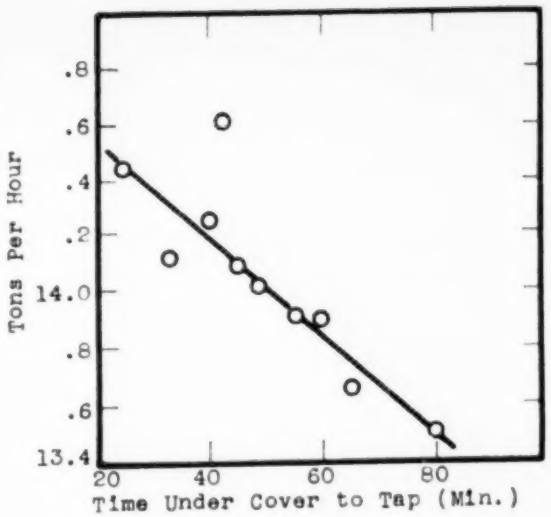

Fig. 10—The importance of melt-carbon control on electric furnaces is emphasized by the effect of time under cover to tap on tons per hour.

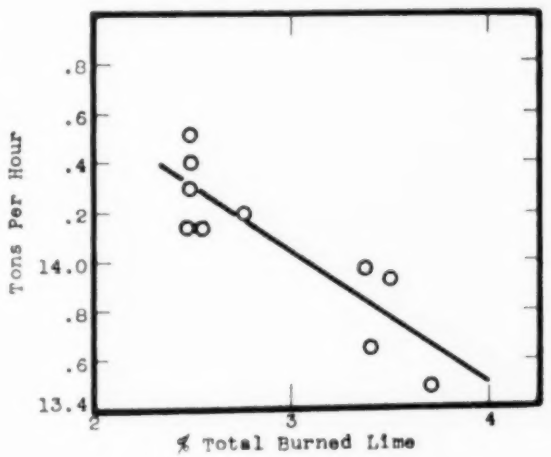

Fig. 11—Amount of burned lime should be held to an absolute minimum because of its effect on tons per hour.

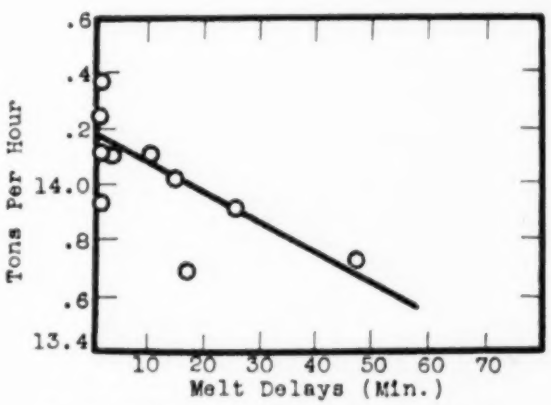

Fig. 12—Effect of melt delays on tons per hour are shown. Melt delays were mainly power demand delays on the furnace.

Automatic Zinc Sampler Saves Handling Time

by Fred J. Meek

Fig. 1 — Conversion to use of the fork truck and automatic spelter sampler has resulted in an overall saving of about 60 pct in handling metal from the furnaces to the railroad cars.

CONVERSION from industrial railway and hand handling of slab zinc to fork truck handling called for an improved method of sampling to replace the old drill press method. American Zinc Co. of Illinois' solution to the problem is an automatic sampler capable of taking two simultaneously drilled samples from a 44 plate bundle, while positioned under the drill guides by the fork truck. The drilling is done as the bundle is raised off the metal scales. The operation of the drills is by a suspended push button, touched by the fork truck operator by moving his left hand a few inches from the steering wheel. The whole operation is a natural action. It adds little to the job of transportation and weighing —except for positioning, pressing the starting buttons, and waiting for the completion of the automatic drilling cycle.

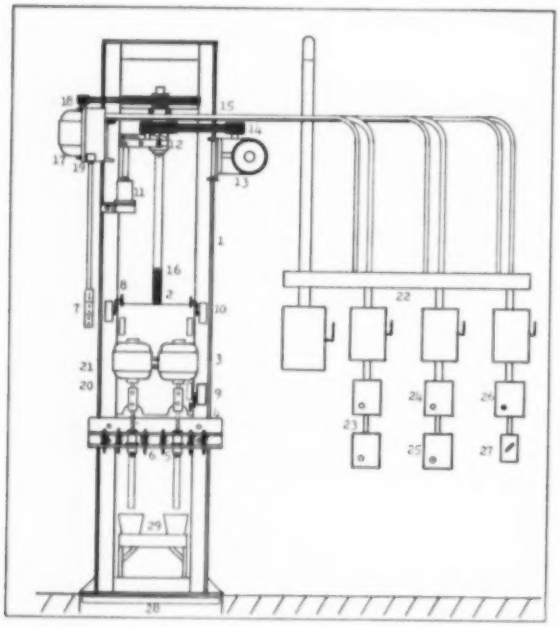

Fig. 2—The sampler consists of: 1—Frame and slide plate guides, 2—slide plate, 3—drill motors, 4—drills, 5—drill guides and sample chutes, 6—holding pins and springs, 7—start-stop buttons, 8—up-motor limit switch, 9—down-motor and clutch limit switch, 10—drill control switch, 11—clutch selenoid, 12—down-clutch, quill, and shifter, 13—down-gear motor, 14—drive, 15—anti-friction bearing and support, 16—thread bar, 17—up-motor, 18—drive, 19—test terminals junction box, 20—anti-friction thrust bearing, rear, 21—thread bar nut on slide plate, rear, 22—fused disconnect switches, 23, 24, 25, 26—magnetic starters for drill motors, down-gear magnetic motor, clutch selenoid, and up-motor, 27—inching switch for drill removal, 28—scale platform, 29—sample pans.

Fig. 1 is the twin drill unit constructed in American Zinc shops after considerable pilot test work. Conventional parts are used except for the drill guides and chip collecting cups with chutes, as illustrated by the sectional drawing in Fig. 2. The apparatus is principally a simple motor operated raising and lowering device. Much experimenting was required to arrive at the production of chips that would flow down the delivery chutes. To date, only the use of standard ½ in. high speed twist drills driven at 1760 rpm with a feed of 0.0017 in. per revolution seems to produce chips instead of spiral curls in drilling spelter either hot or cold. Stainless steel guide bushings have given the best nongalling, nonseizing service for this use. The guide bushings must be without lubrication to avoid contamination.

The drilling operation, while set in motion by a push button, is further controlled as to feed, drill rotation, stopping, withdrawal, stopping of withdrawal and stopping of drill rotation by standard limit switches and a series of magnetic starter switches interlocked or actuating one another. A slow down-feed is achieved by a motor reducer drive which is de-clutched on the up-run. A fast withdrawal is attained by a direct v-belted motor which is never de-clutched, but runs slowly backward on the down-run. To steady the plate bundle and permit drilling on an uneven pile, the drill guides and a number of pointed steadying pins are pressed downward against the raised load by heavily compressed springs. A manual switch on the control panel is used for *inching up* enough for new drill insertion.

The combined conversion to transportation by fork truck and the use of automatic sampling has reduced the crew size from eight men to two men and has eliminated an industrial locomotive, rolling stock, and some other equipment. Two fork trucks, plate stacking racks, and the automatic sampler have been added. The result is an overall saving of about 60 pct in handling metal from the furnaces to railroad cars.

FRED J. MEEK is Plant Engineer of American Zinc Co. of Illinois, Fairmont plant, East St. Louis, Ill.

Residual Stresses Introduced During Metal Fabrication

by Kent R. Van Horn

RESIDUAL stresses in metals operate under a cloak of mystery, as they have neither been seen in the laboratory nor detected by means of the microscope. In spite of their phantom-like nature, they frequently exert metallurgical effects that cannot be ignored. In some cases the results have been detrimental, causing rejections or premature failures, but frequently the effects have been highly beneficial to the producer or consumer of metal products. First, however, what is a residual stress?

When a metal is plastically deformed by bending, rolling, pressing, or by a phase transformation or precipitation from solid solution, or by a sharp temperature gradient resulting from nonuniform cooling, quenching, or welding, it remains in a state of strain. The strains or strain gradients produced by such operations and retained after all external forces are released are known as residual strains, and the accompanying stresses as internal or residual stresses.

Many defects or failures in metal products have been ascribed to residual stresses, sometimes erroneously, because there was no other apparent explanation after the usual metallurgical tools of diagnosis had been applied. For example, during World War II, the forged aluminum alloy aircraft cylinder head in the reciprocating engine began to replace the cast head with the familiar cooling fins. The fins were machined in the solid forged head by an ingenious milling operation. One plant reported an epidemic of excessive distortion during the delicate high-speed milling. A thorough examination revealed that the composition, heat treatment, mechanical properties, and metallurgical quality of these heads were comparable to those of forgings that machined satisfactorily. It was then claimed that the cause of the machining difficulties was connected with residual stresses resulting from the quenching during the solution heat treatment. An elaborate stress analysis actually demonstrated, however, that the magnitude of residual cooling stresses was lower in the cylinder heads which machined poorly than in those which were satisfactory in this respect. Subsequent tests proved that the machining problems in this case originated from variations in the tools and tool design.

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Sources of Residual Stresses in Metals

Residual stresses are of two origins—mechanical and thermal. Thus, stresses may be produced in a metal by any cold-working process. The distribution and magnitude of these mechanically produced stresses can be calculated in a satisfactory, although approximate, manner for such simple cases as bending, torsion, and expanding of tubes. However, most manufacturing processes are too complex, and the original stress-strain relations in the products are not sufficiently known to permit calculation of the resulting residual stresses. Also, a specific process, such as wire drawing, may vary in complexity or uniformity of working, and large or small residual stresses may result, depending on the conformation of the dies and other features of the working process. Neither substantially unidirectional deformation, such as can be imparted by stretching a metal product having essentially the same mechanical properties throughout the cross section, nor deformation

The Transactions papers appearing in the Journal of Metals during 1953 will subsequently appear in AIME Transactions Volume 197, and may be permanently referenced to that volume.

Fig. 1a—Stress corrosion crack in surface of tubular spar chord cold-worked after heat treatment. X5. Area reduced approximately 35 pct for reproduction.

Fig. 1b—Macrograph of crack revealed in (a) just below the surface. Crack is parallel to axis of tube. E. H. Dix, Jr.[6] X20. Area reduced approximately 35 pct for reproduction.

at sufficiently high temperatures followed by slow cooling will create appreciable residual stress.

At sufficiently high temperatures, residual stresses are relieved by plastic flow. Thus, stresses introduced by cold working during fabrication are erased during a high temperature heat treatment; but the subsequent cooling may or may not produce new stresses, depending on the rate of cooling. A metal piece heated and then cooled very slowly remains free from appreciable stresses. Furthermore, as long as the magnitude of any stress is less than the elastic limit at the specific temperature, the stresses are dependent only on temperature gradients and disappear completely on cooling to room temperature or an equalized temperature. The distribution and magnitude of the stresses may be appreciably affected if some sections yield during either heating or cooling. These direct thermal stresses are an important cause of the cracking in steels, which may occur in an article undergoing temperature changes. During quenching the colder surface zones are stretched beyond the yield strength because their normal thermal contraction is restricted by the retarded contraction of the hotter interior zones. When the temperature of the interior zones subsequently approaches that of the surface layers, the previous permanent stretch results in compressive stresses in the outer zones when they attempt to follow the delayed thermal contraction at the interior. This leads to the important generalization that the portions which cool more rapidly retain compressive stresses, whereas the portions which are the last to attain room temperature contain balancing residual tensile stresses; that is, in a rapidly cooled part the surface layers generally contain residual compressive stresses and the core or center tensile stresses. Thus, solution heat-treated aluminum alloy products and many heat-treated products of other metals contain compressive stresses in the exterior layers. This is a highly advantageous stress distribution for the accommodation of external service loads, whereas residual surface tensile stresses, on the contrary, would normally be additive to the service stresses and contribute to cracking or failure. Of course, the residual stress pattern of heat-treated and quenched products may be rearranged by subsequent machining or cold-working operations. Also, the conventional distribution resulting from thermal contraction during quenching may be considerably distorted if a phase transformation interferes with the thermal contraction, as in some carbon steels. Thus, residual tensile stresses can be produced in surface layers of certain quenched steels and, depending on the magnitude, may even cause quenching cracks.

A variety of residual stresses are derived indirectly from deformations produced during cooling. These cooling stresses may originate from, 1—quenching, 2—phase transformation, 3—constituent precipitation, 4—welding, and 5—casting (generally low compared to other sources). All of these stresses result from nonuniform thermal contraction or a volume change during a phase transformation, within the temperature range of cold work.

There are, of course, many comprehensive surveys of the origin of residual stresses in metals available in the literature.[1, 2]

Beneficial and Detrimental Residual Stresses

Residual stresses are frequently suggested as likely sources for some of the difficulties encountered in the machine shop or fabricating plant. In fact, many designers consider residual stresses to be undesirable and believe that procedures should be initiated to eliminate residual stresses in metal products at any cost. Whether or not the residual stresses are actually undesirable can only be ascertained by stress analysis, which may be expensive and sometimes impossible. Castings, extrusions, or forgings generally have complex shapes that do not permit analysis of the stress distribution. The measurement of residual stresses in metals is more difficult, as a general rule, than the determination of the effects of external or service loads.

Residual stresses may have a beneficial as well as a deleterious effect. Some of the advantages of residual stresses that have been commercially utilized have been summarized by your lecturer and Dr. G. Sachs:[1]

1—Stresses produced by plastic expansion are used to increase the strength of gun barrels and pressure vessels (auto frettage). The strength of rotating wheels can also be enhanced by a previous overloading.

2—Stresses imposed by shrink fitting are also employed to increase the strength of gun barrels.

3—Stresses formed by shrink fitting or the introduction of inserts are utilized to improve the service life of extrusion cylinders, forging dies, and drawing dies.

4—Stresses introduced by the quenching of most metal parts probably have a beneficial effect on the fatigue strength.

5—Stresses derived from local deformations produced by mechanical surface treatments, such as surface rolling, shot or hammer peening, ball pressing, etc., reduce to a considerable extent the injurious effects of notches, corrosion, and chafing on the fatigue strength.

6—Stresses resulting from stretching, bending, twisting, and overloads in various types of service applications are used to advantage.

In most of these applications residual compressive stresses are formed in the surface layers where high tensile stresses may be produced by the service loads. The beneficial stresses decrease the magnitude of the resultant surface stress in the case of a static loading; and in fatigue the mean stress in the fatigue cycle is displaced toward the compression side of the stress diagram, resulting in an improvement in fatigue life.

The principal detrimental effects that may accompany residual stress are briefly enumerated:

1—Warping or distortion during machining is related to the magnitude of the residual stresses, their distribution, and the quantity and location of the removed metal or the overloading of the part in the fixture.

2—Fire cracking and stress cracking may occur during the soldering and brazing of cold-worked steels and copper alloys.

3—Materials quenched for the purpose of hardening, such as steels and the aluminum alloys, may crack during or after quenching.

4—Castings and ingots may crack on cooling, storing, or reheating.

5—Fusion-welded structures may crack during welding or in service.

6—Certain alloys, subjected to mild corrosion, crack when sufficiently high surface tensile stresses are present.

7—Steel boilers, subjected to corrosion under stress, crack around riveted or otherwise deformed locations.

The different types of cracking originating from residual stresses have been traced in every case to the presence of high tensile stresses at the point of failure. Some of the cracking phenomena, however, are the result of stresses created by external forces.

Wishart[3] and Richards[4] have recently published comprehensive descriptions of the residual stresses in certain metal products and the mechanical or thermal procedures for producing beneficial or detrimental stresses.

Typical Examples of Residual Stress

Investigation in Metals

Many investigations have been conducted to determine the magnitude and distribution of residual stresses in metal products, to develop methods of stress analysis, to discover practices to reduce or eliminate detrimental stresses, and to develop procedures to impose the type of stresses that would improve the serviceability of the part. Most of this work probably has been done by mechanical engineers rather than by metallurgists. Thus, since 1928, when the papers of the Institute of Metals Division were assembled in a separate volume, there have been only seven papers published on this subject.

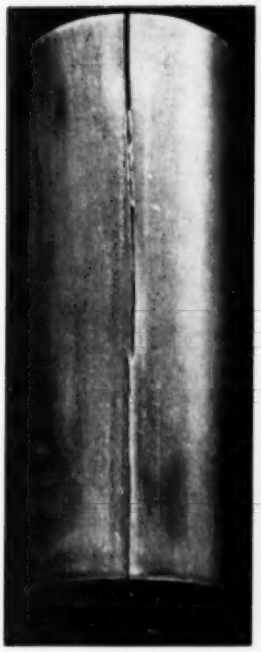

Fig. 2—Season cracking in a brass tube. Courtesy of D. K. Crampton.

The record of the *Transactions* of the American Society for Metals is six papers from 1928 to 1951. This is indeed surprising because of the acute and continuous interest over the years in residual stresses in so many plants that produce, fabricate, or use metals.

Most of the investigations were probably initiated because a part had failed in service and procedures had to be developed to remedy the situation. Several typical investigations of specific interest to the majority of the readers and to the important airframe industry will be described.

Aluminum alloy square tubes were used in the main spar trusses of four-engine airplanes. For ease of fabrication these tubes were manufactured originally as round tubes and then sunk (without a mandrel) to the square shape. With the objective of obtaining maximum tensile properties, this sink from the round to the square tube was performed at room temperature on the completely heat-treated material, thus introducing additional cold work, which resulted in high mechanical properties. However, the plastic deformation also produced a high level of residual tensile stresses on the external surface of the tubes.* The tubes met all chemical and mechanical property specifications and seemed entirely satisfactory for service. Unfortunately, mysterious longitudinal cracks developed in service, Fig. 1. Subsequent fatigue tests of full sections of tube, employing a beam-type specimen with two-point loading, revealed no deleterious effects from the residual stresses.

A laboratory examination of the tubes revealed that the cracks were of an intergranular nature, which suggested that stress corrosion was the cause.[5] This was confirmed by stress corrosion tests which duplicated the type of crack that occurred in service. Also, stress analysis was possible because of the

* In contrast to the high stresses in tubes produced by cold sinking after solution heat treatment, 24S-T36 sheet which is cold-rolled after solution heat treatment possesses a low level of residual stress.

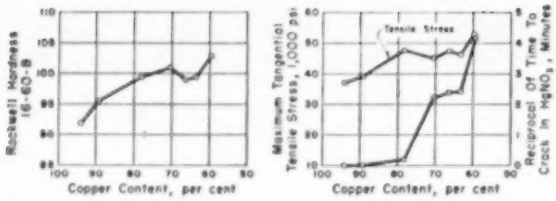
Rockwell Hardness 16-60-B
Copper Content, per cent
Maximum Tangential Tensile Stress, 1,000 psi
Tensile Stress
Reciprocal Of Time To Crack In $HgNO_3$, Minutes
Copper Content, per cent

Fig. 3—Effect of copper content on the magnitude of the residual tensile stress, the Rockwell hardness, and the tendency to season crack in brass tubes sunk from 1.0x0.060 in. to 0.813 in. D. K. Crampton.[6]

relatively simple shape of the tube. The investigation revealed that the residual stress level in the tubes, resulting from the manufacturing process, was extremely high, in many cases as high as 65,000 psi tension, the yield strength of the alloy. This level of residual stress was so high that cracking occurred after a period of time, even when painted tubes were exposed only to ordinary atmospheric conditions. All efforts to prevent cracking by protective films proved futile, and this problem was solved by altering the manufacturing practice to reduce the magnitude of the residual stresses. The change involved was to heat treat after the tube was drawn square, so as to alleviate the residual stresses introduced by drawing from the round to the square shape. No further cracks were encountered in service after this practice was adopted; however, some reduction occurred in the final mechanical properties of the tubes.

This example concerned residual stresses in an aluminum alloy product. However, the occurrence of detrimental residual stresses is not restricted to aluminum alloys but may be characteristic of any metal subjected to certain fabricating conditions. In fact, probably the first recognition of residual stress effects and the principal impetus to the early work in this field resulted from the premature failure in service of brass products possessing residual stresses. Cracking was observed to be most pronounced in cold-worked brasses and to occur occasionally even in the absence of applied loads. This phenomenon, known as season cracking, was detected in brass and copper alloy tubes, Fig. 2, but later was found to occur occasionally in other metals.

Season cracking in brass may be initiated by vibration, oxidation, weathering, and especially by attack of ammonia or compounds of mercury. The cracking tendency in brass increases with the content of zinc (with brasses containing over 20 pct zinc) and depends upon the magnitude of residual stresses.[6] Fig. 3 from Crampton shows the relation of the composition of brass tubes to the tendency to crack, while Fig. 4 illustrates the effect of the degree of sinking on the magnitude of the residual tensile stress (mechanically produced) and the tendency to season crack in high brass tubes.[6] Because of the unsatisfactory character of the data procured from the earlier mechanical sectioning methods of stress analysis, the exact relation between the magnitude or distribution of the residual stress and the tendency to crack has not yet been determined. One expert claimed that a certain type of stress is significant, while another considered that a specific type of stress distribution is detrimental. However, the practical solution to the problem was attained by the selection of immune brass compositions and the introduction of annealing treatments at temperatures that did not produce appreciable softening but reduced the residual stresses to values which were within safe limits.

Residual stresses are produced in the cold drawing of steel rods, and may be high under certain conditions. They may even cause failure of the rods when service stresses are imposed along with even slight corrosive attack, or during machining. The residual stresses can be decreased by slight heating (softening) after drawing; however, this may result in an undesirable reduction in the strength and hardness which were provided by the drawing. A recent investigation[7] revealed that a different distribution of residual stresses could be obtained in drawing steel rods than was previously experienced. Thus, compressive stresses in the interior and tensile stresses in the exterior zones of drawn rods were observed in former experiments. However, Bühler found that the reverse could be obtained, with slight reductions in cross section, by drawing in the opposite direction or pushing through the die. This practice was utilized to reduce the magnitude of residual stresses of drawn rods without any sacrifice in the mechanical properties. Thus, a 0.19 pct carbon steel possessed an 80,000 psi longitudinal tensile stress and 46,000 psi tangential tensile stress at the surface after drawing from 1.9 to 1.8 in. diameter. A subsequent cold reduction of 2.2 pct obtained by pushing through the die, reduced these values to 15,000 and 10,000 psi, respectively.

Among the frequent sources of failure in hardened steel are quenching cracks, Fig. 5. The origin of cracks during quenching of tool steels from the heat-treating temperature was investigated by Scott,[8] who demonstrated that the cracks occurred at surface locations where tensile stresses existed. Scott concluded that tensile stresses at the surface were the result of expansion during the transformation. This effect was more prominent in the specific steels investigated than the stresses formed by deformation arising from contraction on cooling. Scott was able to recommend practical expedients for the control of residual stresses in tool steels and to minimize the quenching cracks. The familiar grinding cracks in steels were also demonstrated by Scott to be the result of tempering of the surface under the grinding wheel, reducing the volume of surface metal and thereby producing surface tensile stresses. Again the cracks occurred in surface layers where high tensile stresses existed.

Methods of Measuring Residual Stress

Residual stresses are generally measured by either mechanical or X-ray methods, although other means have been employed. Unfortunately, the mechanical methods, although extensively used, are destructive in that the procedures consist of removing metal by machining, sawing, drilling, grinding, or etching, and measuring the resulting elastic deformation of the remaining section. X-ray analysis of residual stresses, although nondestructive, has the disadvantage of giving only approximate surface stresses. Surface stresses are often important, but in many applications it is equally necessary to determine the distribution and magnitude of residual stresses in the interior of the section.

In this lecture it is only possible merely to enumerate the available methods for measuring residual stresses, and not to give a detailed description of the theory and techniques of the various procedures. Excellent reviews have been published by Barrett,[9]

Ford,[10] Baldwin,[11] Horger,[12] Sachs,[1, 13] and Lynch,[14] and in the other references to be subsequently cited. Emphasis will be directed toward the methods that are applicable to differently shaped fabricated products, such as solid cylinders, thick or thin-wall tubes, rods, bars, or plates, and to an appraisal of the accuracy of the methods.

Methods for Solid Cylinders and Thick-Wall Tubes: The residual stresses in solid cylinders and thick-wall tubes have been successfully determined by numerous investigators by the Sachs method.[1, 13, 15] The procedure consists of boring on a lathe or drilling out, in small cuts, the interior of a solid cylinder or tube having a length at least three times its

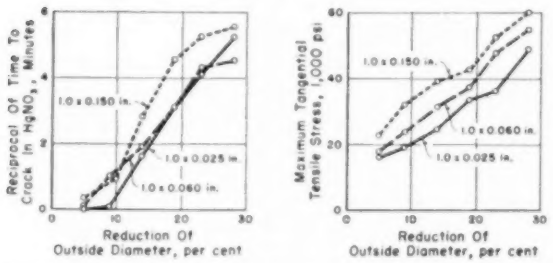
Reciprocal Of Time To Crack In $HgNO_3$, Minutes
1.0 x 0.150 in.
1.0 x 0.025 in.
1.0 x 0.060 in.
Reduction Of Outside Diameter, per cent
Maximum Tangential Tensile Stress, 1,000 psi
1.0 x 0.150 in.
1.0 x 0.060 in.
1.0 x 0.025 in.
Reduction Of Outside Diameter, per cent

Fig. 4—Effect of degree of reduction by sinking on the magnitude of the residual tensile stress and the tendency to season crack in high-brass tubes. D. K. Crampton.[9]

diameter, and measuring the elastic deformation resulting from each boring operation. The recent use of SR-4 electrical strain gages, cemented longitudinally and circumferentially on the exterior surface of the cylinder, has appreciably improved the accuracy of the measurements.

This method permits determination of the three principal stresses in a cylinder. The equations formulated for these stresses are based on the slopes of the curves obtained by plotting deformation (measured changes in dimensions) against bored-out cross section, and are, therefore, subject to some error. Bühler and Schreiber[16] developed a procedure wherein an analytical rather than graphical development of the curves from the data points was employed in an effort to obtain more precise values for the slopes.

With appropriate modifications, the method can also be applied to the removal of metal from the outside surface of a tube or partially bored-out cylinder. Hanslip[17] developed a technique for locating SR-4 gages on the inside surface.

Method for Longitudinal Stresses in Rods, Tubes, and Rails: Where the dominant residual stresses in rods, tubes, and rails are longitudinal in direction, the stresses can be determined easily, although only approximately, by slotting the member longitudinally into many strips of small cross section and measuring the change in length of each strip individually.[18]

Methods for Thin-Wall Tubes: Residual stresses in thin-wall tubes can be obtained by rather simple methods,[19] if the stresses consist of high tensile stresses at the inner or outer surface and high compressive stresses at the other surface. Tangential stresses are evaluated from the change in diameter that occurs at mid-length when a section of tube having a length of at least three diameters is split longitudinally. The deflection resulting from the cutting of a circumferential tongue can also be used. Longitudinal stresses can be obtained from the deflection of a longitudinal tongue. It is generally accepted that the results procured by this procedure permit only an approximate evaluation of the stresses in the tube even when the stresses approach a linear distribution through the thickness. The results are considered to be inaccurate for nonlinear stress distributions.

A more elaborate quantitative method for the determination of residual stresses in thin-wall tube extends the simple procedure described to specimens from which successive surface layers have been removed by machining or etching.

Methods for Bars and Plates: Various methods have been proposed to investigate the stresses in bars and plates. Where the stresses are reasonably uniform through the thickness of a plate, a suitable number of small pieces, oriented in the direction of the principal stresses, are cut from the plate. Each section should contain appropriate gage marks or SR-4 strain gages on which measurements are made before and after the removal of the pieces.[20, 21] If each piece contains only a single gage line, the sections should always be cut in pairs normal to each other, in order to evaluate the biaxial stress conditions in the plate. Another practice is to employ double gage lines, perpendicular to each other, inscribed on each piece. When the directions of the principal stresses are unknown, a rosette method is used with three or more strain measurements made at appropriate angles to each other to permit determination of the magnitude and direction of the principal stresses. Agreement has not yet been reached as to the most satisfactory type of cut-out pieces for this method.

When the stress distribution through the thickness of a bar is desired, the usual procedure is to remove layers from one side of the bar by machining or etching and measure the elastic deformation of the bar after the removal of each layer.[22, 23] The deformation of the bar can be determined either by a

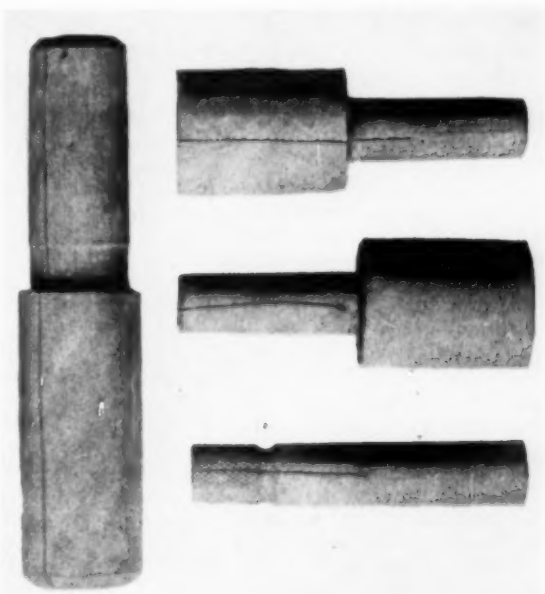

Fig. 5—Quenching cracks in hardened steel plug gages. Cracked from tensile stress at the surface. Deep etched to develop cracks. H. Scott.[9]

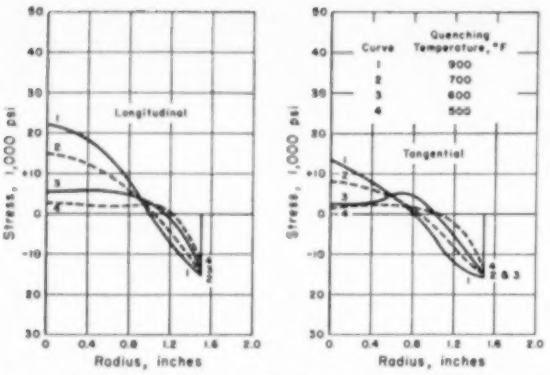

Fig. 6—Effect of quenching temperature on the magnitude of the residual stresses in alloy 56S cylinders, 3.0x9.0 in., quenched in water at 76°F.

sagitta gage, which measures the middle ordinate of a known chord, or by SR-4 gages cemented to the side opposite to the one being machined.

Combinations of these methods can also be adapted for the determination of residual stresses throughout the thickness of a plate.[24] Narrow blocks are removed from the plate in the directions of the principal stresses, and then the strains remaining in the blocks are relaxed by removing thin layers from one side. By adding to the residual strain distribution (obtained from the layer-removal method) the strain distribution relieved when the block is removed from the plate, it is possible to calculate the residual stresses. By selecting blocks in two or more directions, the biaxial stress conditions in the original plate can be evaluated.

In the case of sheet, the magnitude and distribution of biaxial stresses through the thickness may be determined by removing thin layers from one surface of the sheet and measuring the change in curvature of the sheet in the direction of the principal stresses.[25]

Methods of Determining Residual Stresses by Measuring Deformation Around Drilled Holes: A mechanical method for determining residual stresses which does not completely destroy the part to be investigated was devised by Mathar.[26] Basically, the procedure consists of drilling a hole and measuring the deformation on the surface of the metal adjacent to the hole. Mathar employed a mechanical extensometer, and therefore the precision of the results may be questioned. Subsequent work indicated that the use of electrical-resistance strain gages offers more promise for this method. At present, the procedure is restricted to surface stresses or to applications where the stresses are approximately uniform through the thickness.[26, 27] The method has not as yet been extended to the determination of stress distribution where the values vary with depth.

A rapid qualitative survey of residual stresses can be obtained by the use of brittle lacquer to reveal the nature of the stresses relieved by drilling a hole.[28] This procedure will indicate the locations of appreciable residual stresses, the directions of the stresses, and the type of stress at each point.

X-ray Diffraction Methods: The X-ray diffraction method for measuring residual stresses has received considerable attention in recent years.[29–31] In this procedure it is possible to measure the distance between atoms in metal crystals; the interatomic distance is then used as a gage length for the determination of elastic strains. There are numerous modifications that permit the measurement of the sum of the principal stresses at the surface, or the stress component in any direction in the surface layer, or the direction and magnitude of the principal stresses at the surface. The method has the advantage of being nondestructive but is limited to determining the stresses at the metal surface. Attempts have been made to measure stresses below the surface by determining strains at the bottom of a drilled hole, but it is thought that such a procedure is not reliable because of the stresses relieved by drilling the hole, and the possible localized deformation of the metal during machining.

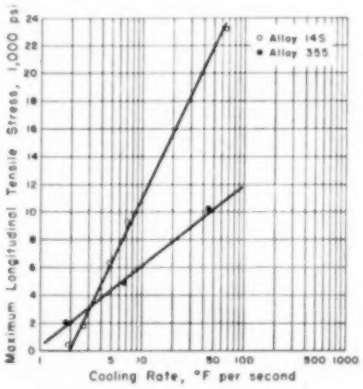

Fig. 7—Effect of quenching rate on the maximum residual longitudinal tensile stress in alloy 14S and 35S cylinders, 3.0x9.0 in., quenched from 935° and 980°F, respectively, in various media.

Other Methods: Methods other than mechanical or X-ray diffraction have occasionally been utilized to determine residual stresses. Measurements of magnetic properties, electrical resistivity, and internal friction have been used and are, in general, qualitative in nature.[32]

Critical Appraisal of Methods for Measuring Residual Stresses

The mechanical methods of determining residual stresses require that the stress equilibrium be disturbed and readjusted by removing metal, and the resulting elastic deformation of the remaining section measured. It is realized, of course, that the mechanical methods are accurate only if no stresses are introduced or relieved by the removal operation itself. Since the metal is generally removed by machining, sawing, drilling, boring, or grinding, some doubt exists as to the reliability of the results obtained from these methods.[33] Etching has been employed to remove metal, but there is the possibility of chemical attack along the grain boundaries of a surface containing residual tensile stresses, which would relieve stresses to a greater depth than intended.

The machining operations used in the mechanical methods tend to increase the temperature of the part being machined. Precautions should be exercised to reduce to a minimum any change in temperature. It is also important that the strains be measured at a constant temperature or that adequate

corrections be applied for any room temperature variations.

Where residual stresses are determined by the removal of successive layers, it is assumed that the stress is uniform throughout the thickness of the layer. This assumption may cause erroneous results where a sharp stress gradient exists. Such gradients occur, for example, at a shot-blasted surface where the stress changes from a high residual compressive

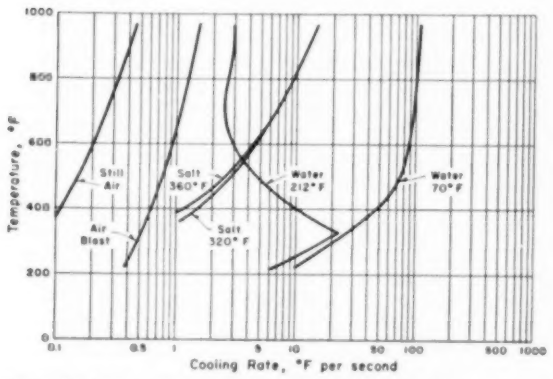

Fig. 8—Cooling rates on alloy 61S sections, 2.25x3.0x7.0 in., quenched from 970°F in various media.

stress at the surface to a relatively low tensile stress at a distance of about 0.020 to 0.030 in. below the surface. Steep stress gradients may also exist on the surface of roller leveled plate. When the stresses in such a plate are determined by removing small sections from the plate, it is desirable that the piece be as small as possible. One limitation on the length of the piece is the gage length by which the strains are measured. For this reason, electrical-resistance strain gages, having an effective gage length as small as 0.06 in., offer a decided advantage over the hand-type mechanical strain gages, where the smallest gage length available for this type of work is about 2.0 in.

The mechanical methods of measuring residual stresses are based on various assumptions, and therefore it is imperative that the limitations of the different procedures are recognized. For example, the Sachs boring-out method, requiring the selection of a cylinder or tube having a length at least three times its diameter, assumes that the stresses have rotational symmetry about the axis and are uniform along the length. If this were not the case, the results would represent only some mean value of the actual stresses.

Not only will the accuracy of the results obtained by the mechanical methods vary with the procedure employed, but the accuracy will also be affected by the dimensions or geometry of the piece to be investigated and the magnitude and distribution of the stresses. For example, the residual stresses were determined in a 0.5x0.75x6.0 in. block from alloy 75S-W as-heat-treated rolled plate by the layer-removal method. Successive layers were machined from the 0.5x6.0 in. surface, the thickness of the first layer being 0.025 in. The strain relaxed on the side opposite the one being machined by the removal of the first layer was 100 microin. per in., equivalent to an average of 14,000 psi compression in the layer removed. Calculations revealed that if the error in this measured strain was ±10 microin. per in. and the error in measuring the thickness of the block before and after the removal of the layer was ±0.0005 in., the residual compressive stress in the layer removed would be between 12,000 and 16,000 psi.

Since the X-ray method is restricted to the measurement of stresses on the surface, and the mechanical methods require extrapolation of stresses to the surface, it is difficult to compare the two procedures and appraise the relative accuracy. The X-ray method requires a refined technique in preparing the metal surface and in making the measurements. The metal must be fine-grained, of uniform composition, and free of minute stress variations. If the grain size is too large, the diffraction lines are spotty or not of uniform width, and therefore cannot be measured precisely. On the contrary, a grain size which is too fine produces broad lines and consequent inaccuracy. Thomas[20] compared the stresses measured by X-rays in steel with mechanically imposed stress values and found that the stresses obtained from the X-ray were about 30 pct higher than those calculated from the actual loads. Some of the possible sources of error in the X-ray method were encountered in this investigation, so that the total discrepancy may not be representative of the optimum conditions for X-ray diffraction. Under conditions giving sharp diffraction circles, the line widths can be measured with a precision of about ±0.01 in., representing an accuracy in stress values of ±1,500 psi. As the line becomes broader, the precision decreases considerably.[21]

Effects of Fabricating Practices on the Residual Stresses in Aluminum Alloys

The majority of the investigations involving the determination of residual stresses in fabricated metal products was initiated because of the failure, cracking, or excessive distortion of a part, and the possibility that residual stresses contributed to, or were responsible for, the difficulty. Thus, exhaustive qualitative investigations have been conducted on axles, gears, propellers, spars, tubing, and weldments. In general, mechanical methods of stress analysis were employed, and usually the results culminated in the adoption of a different fabricating practice. There have been few quantitative investigations of the effects of various fabricating conditions and metallurgical factors on the magnitude and distribution of residual stress in metals published in this coun-

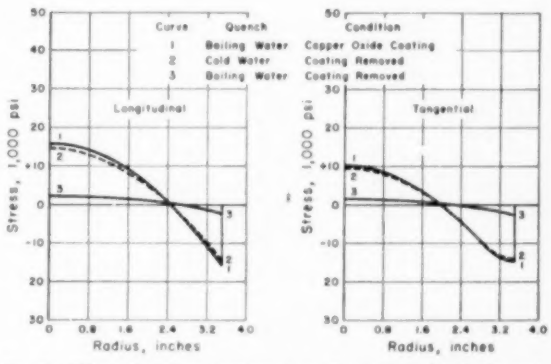

Fig. 9—Effect of surface treatment on the magnitude of the residual stresses in alloy 14S cylinders, 7.0x7.0 in., quenched from 940°F in boiling or cold water.

try. However, the literature reveals that there have been extensive investigations conducted on various steels in Germany.

This lecture will report briefly on an investigation of the effects of quenching temperature, quenching rate, section size, composition, and tensile properties on the magnitude of residual stresses in cast and wrought aluminum alloy products. In addition, the effects of reheating time and temperature on the magnitude and distribution of retained stresses will be discussed. Although the work was performed on aluminum alloys, the significance of the various fabricating factors and the general conclusions should apply to all metals. In the investigation, several hundred cylinders were analyzed by the Sachs[15] boring-out method. The length of most of the cylinders was generally three times their diameter. The curved surfaces of the cylinders were machined and ground to a fine finish, while the bases were machined and finished on a lapping plate. The cylinders were measured in a constant temperature room on a comparator, standardized by the most precise type of gage blocks available. Special jigs were constructed

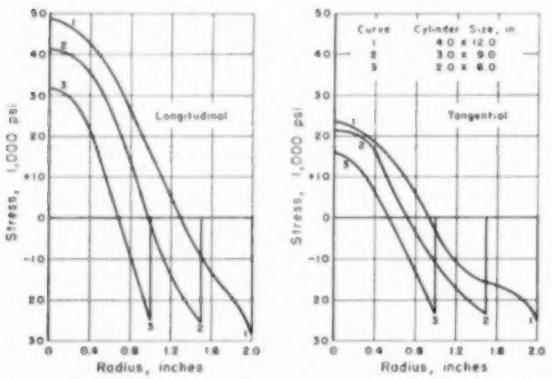

Fig. 10—Effect of section size on the magnitude of the residual stresses in alloy 14S cylinders quenched from 940°F in water at 70°F.

to hold the various sized cylinders rigidly during the boring operations. Care was exercised to use light cuts during boring, and auxiliary cooling was employed to prevent heating of the cylinders. The use of small cuts increased the number of measurements, thereby improving the accuracy of the data, although this practice added appreciably to the cost of the tests. The measured elastic deformations, resulting from the readjustment of stress equilibrium produced by the boring operations, were converted by the equations formulated by Sachs to longitudinal, tangential, and radial stresses. The stress distribution diagrams were all checked by planimeter measurements to determine if the stresses balanced.

Inasmuch as the high strength aluminum alloys are solution heat-treated at relatively high temperatures, the residual stresses formed during the fabrication of castings, bars, extrusions, forgings, etc. are relieved during the heat treatment. However, the quenching or cooling from the solution heat-treating temperature produces residual stresses which may be either large or negligible, depending on the various factors which will be discussed. The resulting stress pattern or distribution is always the same and relatively simple. Longitudinal and tangential compressive stresses exist in the exterior or surface layers of solid shapes or cylinders, and tensile stresses in the core or center. The radial stresses are tensile at the axis and zero at the surface. The residual stress pattern of heat-treated hollow cylinders reveals longitudinal and tangential compressive stresses on both the exterior and interior surfaces with tensile values between. The residual stress distribution in sunk tube is, of course, different from that in quenched tube. The longitudinal and tangential stresses are tensile in the surface layers and compressive on the interior surface. The radial stresses are compressive in the intermediate layers and zero at the interior and exterior surfaces.

Effect of Quenching Temperature: The effect of quenching temperature on the magnitude of the residual stresses in alloy 56S** solid cylinders, 3.0x9.0 in., quenched in cold water at 76°F, is illustrated in Fig. 6. Alloy 56S, essentially a solid solution alloy at all temperatures, was selected for this experiment in order to eliminate precipitation effects during quenching. Varying the quenching temperature from 900° to 500°F decreased the rate of quenching and reduced the longitudinal and tangential compressive stresses in the surface layers of the cylinders by 25 and 13 pct, respectively, and both the longitudinal and tangential tensile stresses in the center by approximately 88 pct. The distribution diagrams also revealed that when the quenching temperature was 600°F or lower, the maximum tensile stress was displaced from the center of the cylinders.

Effect of Quenching Rate: The magnitude of the residual stresses in the quenched aluminum alloy cylinders depended directly on the cooling rate prevailing during the quench from the solution heat-treating temperature. The relation between the quenching rate and the magnitude of the residual stresses in alloy 14S and 355 solid cylinders, 3.0x9.0 in., quenched from 935° and 980°F, respectively, is represented in Fig. 7. In this illustration, only the maximum longitudinal tensile stress at the center of the cylinder was plotted. The highest residual stresses were produced when the cylinders were quenched in cold water, intermediate values when quenched in hot oil, molten salt, or hot water, and very low stresses when quenched in boiling water or by an air blast. The various quenching media employed (cold water, boiling water, oil, moving air, etc.) produced different cooling rates ranging from approximately 100°F per sec to 2°F per sec. Fig. 8 shows the cooling rates obtained for alloy 61S sections, 2.25x3.0x7.0 in., quenched from 970°F in various media.

The significant effect of the quenching rate on the magnitude of the residual stresses was again clearly demonstrated in an investigation of surface treatments on alloy 14S solid cylinders. A cylinder with a surface layer of black copper oxide, produced by the reaction of an alkaline etchant, was found to have the same cooling rate when quenched in boiling water as that of a cylinder with the coating removed when quenched in cold water. The cylinders were quenched from 940°F. Stress analysis revealed that the magnitude and distribution of the residual stresses in the two cylinders were identical, Fig. 9. This marked effect on cooling rate and stress magnitude is attributable to the wettability of the copper oxide coating. The residual stress pattern for a

** The alloy and temper numbers in this paper refer to Aluminum Company of America designations. The compositions and temper treatments of the alloys are printed in the 1948 edition of *Metals Handbook* published by the ASM.

similar sized cylinder with the coating removed, that was quenched in boiling water, is also included in Fig. 9.

Effect of Section Size: The effect of section size on the magnitude of the residual stresses was investigated in 2.0x6.0, 3.0x9.0, and 4.0x12.0 in. alloy 14S cylinders quenched from 940°F. Increasing the section size of cylinders quenched in water at 70°F appreciably increased the maximum longitudinal, tangential, and radial tensile stresses, and to some extent the maximum longitudinal compressive stress. The maximum tangential compressive stress values remained about the same, Fig. 10.

This effect of section size on the magnitude of the residual stresses is partially explained by the data[34] in Fig. 11, which records the temperatures at the center of a 0.75 in. diam rod, and at the center and other locations in a 4.0 in. diam rod, of alloy 75S during quenching from 875°F in water at 70°F. The curves show a marked temperature gradient in the 4.0 in. rod during the quench. It is revealed that the center of the 0.75 in. rod cooled much more rapidly than the center of the larger rod, in fact even faster than the surface zone of the larger rod. It may be

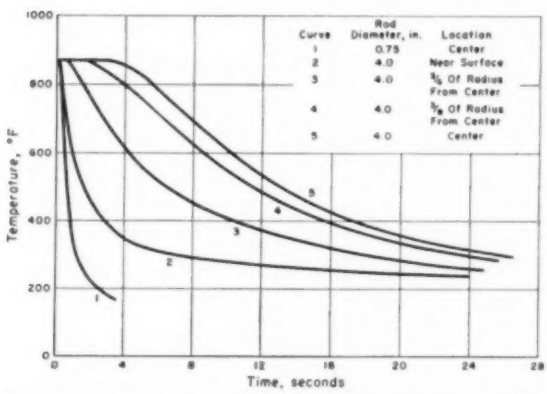

Fig. 11—Cooling curves for 0.75 and 4.0 in. diameter extruded alloy 75S rods quenched from 875°F in water at 70°F. Thermocouples located at various distances from center of 4.0 in. rod. W. L. Fink and L. A. Willey.[34]

concluded that this would result in a greater, and certainly more prolonged, differential in temperature between the surface and interior zones in the larger rod than in the smaller. Thus, higher stresses would be expected in the larger rod, since the temporary difference in temperature between the center and surface zones is the basis of the formation of thermal stresses, as explained in the introductory pages of this lecture.

The effect of section size can be definitely minimized by employing a slow quenching rate, such as that provided by boiling water, Fig. 12. A comparison of Figs. 10 and 12 demonstrates the advantage of a boiling water quench for obtaining a low level of residual stress. The benefit of the boiling water is ascribed to the slow cooling rate in the critical cooling range, resulting from the prolonged occurrence of the vapor phase or envelope surrounding the cylinder.

Effect of Composition: The magnitude of the residual stresses in the solid cylinders varied considerably with the different cast and wrought aluminum alloys. Cylinders, 3.0x9.0 in., of all the alloys were quenched from the respective commercial

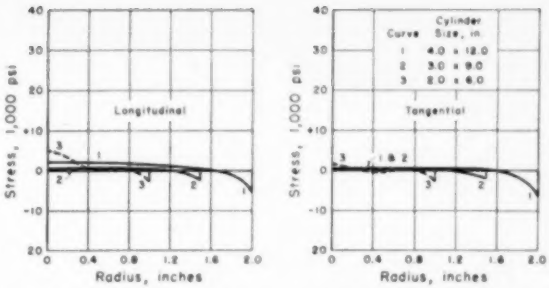

Fig. 12—Effect of section size on the magnitude of the residual stresses in alloy 14S cylinders quenched from 940°F in boiling water.

heat-treating temperatures in boiling water or water at 70°F.*** The stresses developed were considered to depend on several properties or characteristics of the specific alloy. Thus, for a given strain, the higher the value for Young's modulus of elasticity, or the greater the proportional limit and yield strength of the alloy, the higher were the residual stresses, providing the other properties did not vary. Other properties which would be expected to contribute to a large strain, and therefore higher stresses, are: a high coefficient of thermal expansion, a low thermal diffusivity,† and a high elevated temperature yield strength.

*** The cold water quench at 70°F was employed to evaluate the effect of composition factors and does not represent commercial practice for aluminum alloy castings and forgings. Therefore, the residual stresses indicated in Figs. 13 and 14, resulting from quenching alone, are appreciably higher than expected in commercial castings and forgings.

† $\text{Thermal diffusivity} = \dfrac{\text{Thermal conductivity}}{\text{Specific heat} \times \text{density}}$

The composition factors appeared to vary in their relative influence on the magnitude of the residual stresses that were developed in the various aluminum alloy cylinders. The coefficient of thermal expansion seemed to be one of the most significant properties. For example, alloys 32S and A132 have fairly high yield strengths and the highest modulus of elasticity values, but the lowest coefficients of thermal expansion, and the stresses developed in these alloys by a water quench at 70°F were the lowest for any of the aluminum alloys investigated (17,900 psi and 20,700 psi maximum longitudinal tensile stress, respectively). Furthermore, alloy 220 with the lowest modulus of elasticity value but the highest coefficient of thermal expansion, developed high residual stresses (39,400 psi maximum longitudinal tensile stress).

The elevated temperature yield strength also appeared to be one of the potent factors. For example, alloys 14S and 142, with average values for the coefficient of thermal expansion, modulus of elasticity, and thermal diffusivity, but very high elevated temperature yield strengths, developed the highest residual stresses, when quenched in water at 70°F, of any of the aluminum alloys tested (41,250 psi and 42,950 psi maximum longitudinal tensile stress, respectively).

Effect of Tensile Strength: It is recognized that the yield strength of an alloy at that temperature during quenching, when plastic flow is completely arrested, is a significant factor affecting the magnitude of residual stresses, but such data are not available. However, some engineers may raise the

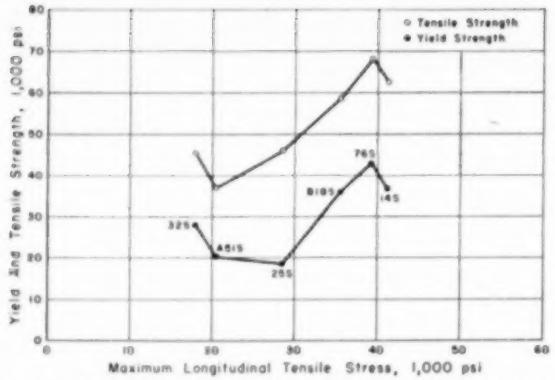

Fig. 13—Relationship of yield and tensile strength (-T4 condition) and maximum residual longitudinal tensile stress in cylinders, 3.0x9.0 in., of various aluminum forging alloys quenched from the respective commercial heat-treating temperatures in water at 70°F.

question of a relationship between residual stresses and the tensile and yield strength at room temperature. Therefore, tensile data were also obtained during the investigations of the effect of fabricating conditions on the magnitude of the residual stresses. Additional cast or wrought solid cylinders of the size used for stress analysis were simultaneously subjected to the same heat-treating, quenching, and room temperature aging procedures. Tensile test bars were machined from identical locations in the cylinders. In general, the tensile properties decreased as the rate of quenching was reduced and as the section size was increased. The magnitude of the decrease varied with the alloy. The results seemed to reveal a trend that the alloys having the higher tensile values, that is, those in the T4 condition,‡ contained the higher residual stresses, Figs. 13 and 14. This relationship was more apparent for the forging than for the casting alloys.

‡ Quenched from solution heat-treating temperatures in water at 70°F and aged at room temperature. The aging time was three days for the casting alloys and five days or more for the wrought alloys.

Distortion During Machining: When the balance between relatively high residual stresses in metal products, especially those having heavy or thin sections, is disturbed by machining, undesirable distortion or dimensional changes may result. Thus, for example, airplane cylinder muffs of alloy 142 distorted to such an extent during rough machining that the final finishing operations could not be performed. Measurements of residual stress revealed a maximum tangential compressive value of 14,000 psi in the 8.5x5.5 in. cylinders, quenched from 960°F in water at 90°F and stress-relieved 9 hr at 525°F, Fig. 15. Adoption of a boiling water quench reduced the residual stresses to a negligible amount and eliminated the distortion problems.

Difficulties were experienced by several customers in the textile industry, from distortion during the machining of extruded shapes of some of the heat-treated aluminum alloys. In some cases, the distortion was so severe that the shape was unsuitable for the intended use. An investigation was therefore conducted on the aluminum alloys 14S-T6, 61S-T6, and 75S-T6 to evaluate various methods of reducing the residual stresses which were thought to be the cause. The effect on residual stresses of quenching rate from the solution heat-treating temperature was investigated for the following quenching media: cold water, cold water spray, boiling water, light oil at temperatures ranging from 70° to 264°F, and an air blast. Different degrees of stretching before artificial aging and reheating treatments after aging were also evaluated.

Since this investigation was concerned principally with deformation during the machining operation, no attempt was made to determine the residual stresses quantitatively. Instead, a procedure was developed which permitted the direct measurement of the distortion of specimens (a complex extruded shape 10 in. in length) resulting from a longitudinal saw cut. All samples were subjected to the same sequence of saw cuts, and the average deformation of several cuts on several specimens was used to measure the tendency to distort during machining.

The type of quench was found to be highly important, with the boiling water quench best and the cold water quench the poorest from the standpoint of distortion. Unfortunately, however, the boiling water quench, because of section size involved, appreciably lowered the mechanical properties of the alloy. Stretching the product was found to be generally effective in reducing the distortion, but stretching alone was in no case sufficient. Reheating

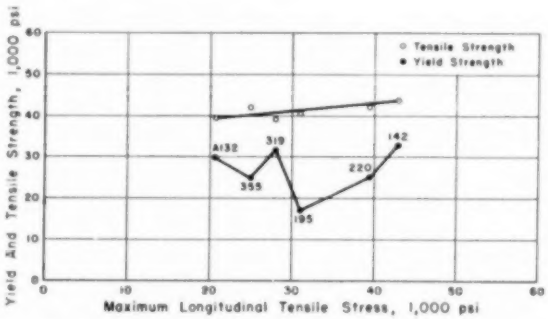

Fig. 14—Relationship of yield and tensile strength (-T4 condition) and maximum residual longitudinal tensile stress in cylinders, 3.0x9.0 in., of various aluminum casting alloys quenched from the respective commercial heat-treating temperatures in water at 70°F.

the product after artificial aging, in the range where the tensile properties would not be seriously impaired, did not significantly decrease the distortion.

After an appraisal of the results of this investigation and considerable experimental work in the fabricating plants, a special metallurgical technique was devised which resulted in sufficiently uniform mechanical properties throughout the cross section so that a controlled stretching operation gave an acceptably low degree of distortion during machining without affecting the final strength of the product. The temper produced by this process is known as -T64 and it applies only to alloy 14S extruded shapes. This product can be used with the assurance that machining operations will not produce any serious distortion.

The cylinder muff and the extruded shape problems illustrate applications where rather high residual stresses were responsible for distortion or change in dimensions of the part during machining. The extent of warpage resulting from residual stresses is also influenced by the design or size of the part. Important factors are a large variation in sectional thickness or high ratio of width to length dimensions and the character and sequence of the machining

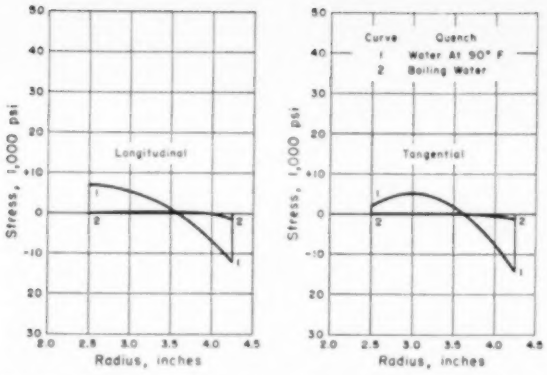

Fig. 15—Effect of quenching rate on the magnitude of the residual stresses in alloy 142 airplane cylinder muffs, 8.5x5.5 in., quenched from 960°F in water at 90° and 212°F and subsequently stress relieved 9 hr at 525°F.

operations. In such instances, intermediate straightening may be necessary, and it is preferable to avoid machining to finished dimensions from one side only. An attempt should be made to balance the machining operations, leaving sufficient allowance to compensate for any final straightening found necessary. However, the residual stress level may be relatively low, but nevertheless substantial warpage may occur during machining or on removal of the part from the clamping device as the result of improper tools or machining practices.

In addition to residual stresses, there are several other sources of distortion or change of dimensions during machining. Careful consideration should be given to cooling the part during machining operations if precise dimensions are to be attained. Aluminum alloys have a high coefficient of thermal expansion, and therefore adequate cooling practices should be employed.

An important cause of distortion in many machining operations is improper jigging or chucking of the part, so that it is elastically deformed or sometimes even stressed beyond the yield strength. Since a good mechanic would adequately tighten the clamps that hold the part during the machining operation, the fixture should be so designed that such tightening does not deform the part. Very high stresses can be produced by improperly designed fixtures, and the stresses may be redistributed in subsequent machining operations. If the part is overheated during machining, the yield strength is reduced by the temperature and, furthermore, the strains imposed by the fixture may be higher. The distortion occurs during machining or upon removing the part from the fixture. Considerable experience in the field has indicated that more distortion or warpage in cast aluminum alloy parts and some forgings has resulted from this cause than from any of the other sources.

Distortion or change in dimensions of parts as the result of permanent growth in aluminum alloys is thought by some to occur at room temperature or on reheating to temperatures up to 300°F. Growth is caused by an advanced stage of precipitation of constituents in the alloy, and definitely does not occur at room temperature. In fact, extensive tests have demonstrated that no significant changes in dimensions have been detected in aluminum alloys from growth, at room temperature or at slightly elevated temperatures. Therefore, the tendency to grow is not a source of change in dimensions during machining or in subsequent storage.

Stress Corrosion Cracking: High residual stresses are known to be an important contributing factor in the phenomenon of stress corrosion cracking. Several applications were previously described where the presence of excessive residual stresses contributed to premature cracking or failure of the part in corrosive or natural environments. An interesting example of a quantitative stress analysis, that revealed high residual stresses promoting stress corrosion cracking, will be discussed.

An unusual type of failure was encountered in the early use of Alcoa 76S, an aluminum-zinc-magnesium forging alloy, for aircraft propeller blades of high strength and hardness with improved abrasion resistance. The propeller blade, having about a 6.0 in. diam shank, was forged solid, solution heat-treated, and artificially aged. Then a tapered hole about 17 in. in length was bored in the center of the shank with the diameter gradually decreasing from about 3.0 in. at the end of the shank as illustrated in Fig. 16. Large cracks occurred during service and were detected when oil from the variable pitch propeller mechanism leaked through the oil-retaining

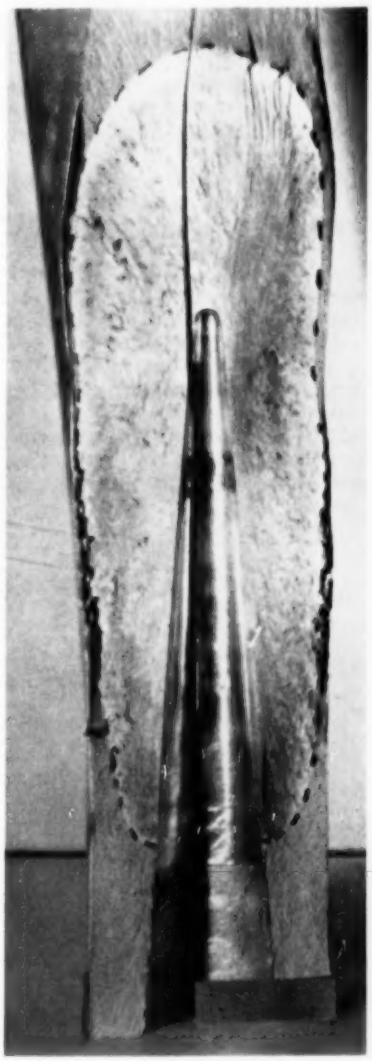

Fig. 16—Stress corrosion fracture (within the dotted lines) of shank of a forged alloy 76S propeller, caused by high residual tensile stresses in surface layers of bored hole resulting from rapid quenching from 860°F. E. H. Dix, Jr.

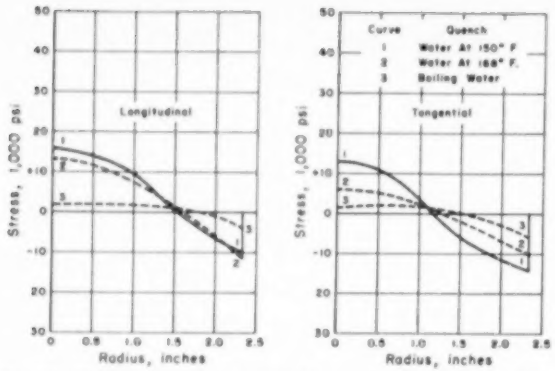

Fig. 17—Effect of quenching rate on the magnitude of the residual stresses in alloy 76S propeller hubs, 4.0 in. diameter x 4.0 in. long, quenched from 860°F in water at various temperatures.

ring into the bore. A crack and the stress corrosion fracture (within dotted lines) are shown in Fig. 16. An investigation revealed that the central portion of the original propeller hub contained high tensile stresses produced by the rapid quenching from the solution heat-treating temperature of 860°F in water at 150°F. The machining of the bore exposed layers at the surface of the hole having high circumferential tensile stresses.

Analysis of residual stresses in sections from alloy 76S propeller hubs, 4.0 in. diameter x 4.0 in. long, quenched from 860°F in warm water at 150° or 168°F and in boiling water revealed that the first two quenches produced a relatively high level of stress, whereas the boiling water quench resulted in low tensile stresses in the center, Fig. 17. Fortunately, alloy 76S is comparatively insensitive to the rate of quenching, and satisfactory mechanical properties can be obtained with the less drastic boiling water quench. This investigation resulted in the commercial adoption of a boiling water quench. As an additional precaution, the propeller manufacturer shot-peened the surface of the drilled bore. The shot peening reduced any possibility of a high interior surface tensile stress and may have imposed a compressive stress. After the introduction of the two procedures, no stress corrosion cracking was experienced, and hundreds of thousands of 76S-T61 propeller blades have been in successful service, beginning in 1942.

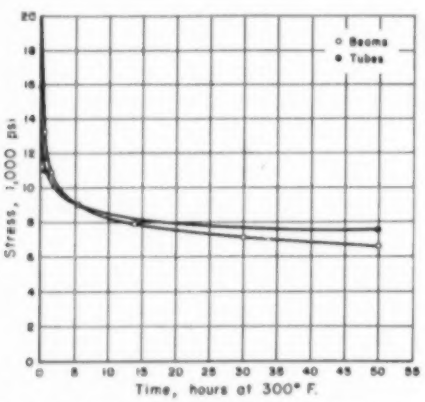

Fig. 18—Relief of stress at 300°F in 52S-H34 drawn tubes and externally loaded 52S-H34 beam specimens, original stresses 15,650 and 27,000 psi, respectively. Tubes 2.75 in. ID, 3.75 in. OD, 6.0 in. long. Beams, 0.25x0.06x12.0 in. Kempf and Van Horn.[35]

Relief of Residual Stress by Thermal Treatments

To insure proper selection of conditions for obtaining optimum combinations of mechanical properties, resistance to corrosion, volumetric stability, and freedom from residual stress problems in heat-treated aluminum alloys, it is desirable to acquire data on the effect of time and temperature on the rate of relief of residual stress. The magnitude of the residual stress can be reduced to a satisfactorily low level by reheating to a temperature at which sufficient plastic flow can occur. However, such stress-reducing methods are not practical in all cases because of the sacrifice in other important engineering properties.

It is recognized that the relief of residual stress involves the phenomenon of flow or creep. Creep characteristics, however, ordinarily are determined by measurement of rate of deformation at constant stress. The relief of residual stress is concerned with flow conditions at relatively constant deformation and decreasing stress. Flow under these conditions is sometimes referred to as relaxation. Relatively little investigational work has been done in this field. There are some indications of a quantitative relationship between relaxation and creep, but the data available at the present time are too meager to permit the definition of any correlation.

The Sachs boring-out method of stress analysis can be applied to the determination of the rates of relief of residual stress in metals. Thus, Kempf and Van Horn[35] presented curves showing the rate of stress relief in heat-treated solid cylinders of alloy 122 and in 52S-H34 drawn tubes for several reheating periods at a specific temperature. The curve for the tubes is reproduced in Fig. 18. Both stress-relief curves revealed that the initial reheating resulted in a rapid decrease of 25 to 50 pct of the original‡ residual stress, and that further reduction occurred much more slowly on extended heating. In general, the higher the temperature of reheating, the greater the initial reduction in stress and the greater the rate of subsequent relief. It is important to observe that these stress-relief curves resemble the relaxation curves reported in the literature.[36, 37] This immediately suggests that a measurement of the relaxation characteristics might be a convenient and more economical means than the Sachs method for determining rates of relief of residual stress in metals. Obviously, the Sachs method would require the careful boring and measurement of a large number of cylinders representing many different periods of heating at various temperatures for all the aluminum alloys. However, the quantitative determination of rates of relaxation is by no means simple, involving as it does the accurate measurement of a varying stress under conditions of relatively constant deformation; also determinations must usually be made at elevated temperatures.

Kempf and Van Horn[35] considered it sufficient to determine at room temperature the variations in stress, with time at elevated temperature, of specimens maintained during the entire operation at a constant deformation. To achieve this end, a fixture

‡ The original maximum residual stress was about 47,500 psi tension in the 122 alloy cylinders and 15,650 psi tension in the 52S-H34 tubes. Subsequent tests demonstrated that the time required to relieve a certain percentage of the residual stress at a specific temperature was independent of the magnitude of the original stress.

was utilized that was developed by Dr. W. L. Fink. The fixture[35] consisted merely of a means for maintaining a small beam of rectangular cross section under constant deformation during reheating, the remaining stress to be measured subsequently at room temperature. Many measurements for different periods of time at a specific temperature can easily be obtained on the same specimen. These tests can be continued until the desired relaxation of stress is achieved. Thus, it is possible to determine the rate of stress relief in a relatively inexpensive manner for different temperatures and periods of time, and for various amounts of imposed stress. Fig. 19, reproduced from this investigation,[35] illustrates data obtained for the relief of several imposed stresses in alloy 122 beams at 435°F for various time periods. Data for several aluminum casting alloys heated at different temperatures were also included in this paper.

Similar stress-relief surveys can be obtained for any metal. Thus, Fig. 20 from Stewart[36] represents the effect of tempering temperature on carbon steel

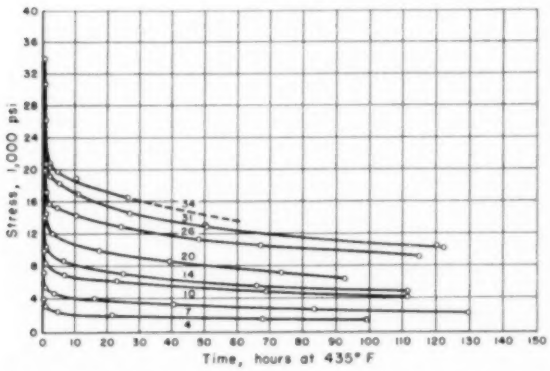

Fig. 19—Relief of stress in beam specimens, 0.25x0.06x12.0 in., of alloy 122 at 435°F. Curves show stress-time relationship for different original loads indicated. All specimens air-cooled from 930°F. Kempf and Van Horn.[35]

boiler plate prestressed in tension to 25,000 psi for various periods of time. In Fig. 20, the stress was constant, while in Fig. 19 the temperature of stress relief was the same for different imposed stresses.

A comparison of the results of the relaxation procedure with those of the Sachs method for determining the rate of stress relief is also shown in Fig. 18. Beam specimens were prepared from 52S-H34 sheet, stressed to about 27,000 psi and reheated for various periods of time at 300°F. The results are represented by open circles in Fig. 18. The curve for the rate of relief of residual stress in hard-drawn 52S-H34 tubes (stress 15,650 psi), determined by the Sachs method, is included in Fig. 18. The resemblance between the two curves is apparent, and undoubtedly is a result of essentially linear distribution of stress in the wall of the tube and, of course, in the stressed beam. Apparently a relationship exists between the rate of relief of residual stresses produced in the cold drawing of the tube and of the stresses imposed by external means in the beam method.

An even better correlation between the Sachs and beam methods for the determination of the rates of stress relief was obtained for alloy 14S. In this case, the residual stresses were produced by quenching

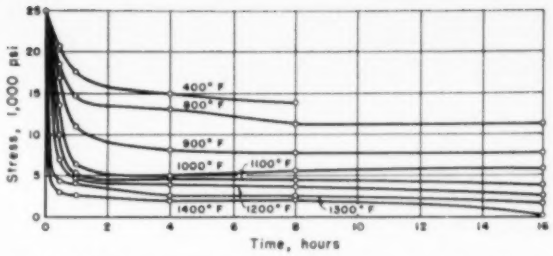

Fig. 20—Relief of stress in 0.5 in. diameter carbon steel specimens of boiler plate prestressed to yield (25,000 psi) before tempering. Curves illustrate stress-time relationship for different tempering temperatures. Stewart.[36]

rather than by mechanical means. These stresses were relieved, measured, and compared with similar stress values in beams imposed by external loads. Fig. 21 shows the results for solid cylinders of 14S quenched from 940°F in water at 150°F and beams stressed to 24,600 psi. The maximum residual longitudinal tensile stress in the quenched 14S cylinders was the same, 24,600 psi. Both cylinders and beams were heated at 437° and 500°F for different periods of time. It was concluded that the beam method should have some utility in arriving at qualitative data for selecting optimum aging or annealing treatments for the various cast and wrought alloys.

Stress-time measurements have now been completed by the beam method for the majority of the cast and wrought aluminum alloys. The amount of stress relief was determined for initially applied stresses of 4,000, 7,000, 10,000 and 14,000 psi at various temperatures, depending on the alloy, for time intervals of minutes up to 100 hr. A typical example of the results for all the original stresses is represented in Fig. 22, including a number of cast and wrought alloys heat-treated at the respective commercial temperatures, quenched in boiling water, and reheated at 482°F, for different time periods. The alloys exhibited different rates of stress relief, showing that composition has an important effect.

In all cases, an appreciable proportion of the stress relief occurred during the first hour of heating. The higher the temperature the greater was the rate of stress relief, both during the initial and subsequent

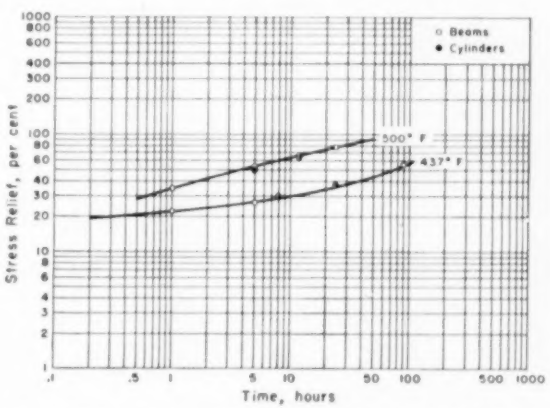

Fig. 21—Stress relief at 437° and 500°F for alloy 14S cylinders, 3.0x9.0 in., and beam specimens, 0.25x0.06x12.0 in., quenched from 940°F in water at 150°F. Maximum residual longitudinal tensile stress in quenched cylinders 24,600 psi and original tensile stress in beams 24,600 psi.

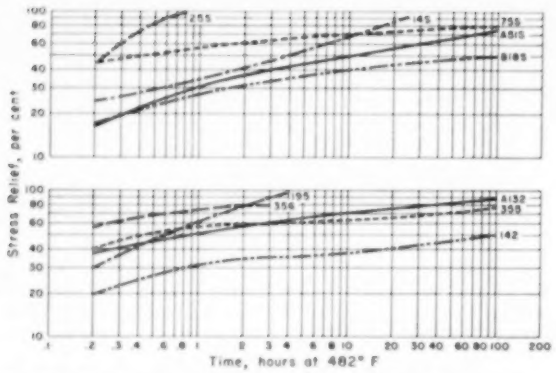

Fig. 22—Relief of stress in beam specimens of various cast and wrought aluminum alloys at 482°F. Original stresses were 4,000, 7,000, 10,000, and 14,000 psi. Beams 0.25x0.06x12.0 in., quenched from the respective commercial heat-treating temperatures of the alloys in boiling water.

heating periods. The stress-time data obtained at the various temperatures for all the alloys demonstrated that in order to obtain a low level of residual stress by relaxation heat treatments, the temperature is more important than the time factor. The effect of temperature on the relaxation rate of three aluminum alloys for a 10-hr heating period is illustrated in Fig. 23. The higher the initial stress, the more rapid was the rate of relief in terms of actual stress. However, the time required to relieve a certain percentage of the residual stress at a specific temperature was independent of the magnitude of the initial stress.

The rate of stress relief varied considerably with the different cast and wrought alloys. The rate of relief was relatively rapid with the essentially binary aluminum-copper and aluminum-magnesium alloys (122, 195, and 220) and with alloys 14S, 25S, 75S, 32S, A132, and 356. The slowest relaxation rates were exhibited by alloys 18S, B18S, 76S, and 142. The very slow rates of relaxation of alloys 18S, B18S, and 142 seemed to indicate that the alloys possessing a high strength at elevated temperatures would also have a slow rate of stress relief. However, this is not always true, because alloys 14S and 122 have rapid relaxation rates.

The close agreement between the stress-relief rates of the wrought alloy 32S and cast A132 of similar composition, and of wrought B18S and cast alloy 142 of the same analysis, indicated that the rate of relaxation is not affected by the type of microstructure or the method of fabrication.

It was thought that a correlation should exist between the relaxation rates and the high temperature creep values for the various aluminum alloys. However, from the limited creep data now available it appears doubtful that such a relation can be established.

The effectiveness of the commercial artificial aging treatments in relieving a substantial percentage of the residual stress depends on the rate of relaxation of the specific alloy. If the alloy is one that exhibits a rapid rate of stress relief, a relatively large percentage of the stress will be released, although the aging temperature may be as low as 300° to 400°F. However, if the alloy is one that has a slow relaxation rate, the low temperature generally employed for aging treatments will relieve only a small percentage of the residual stress.

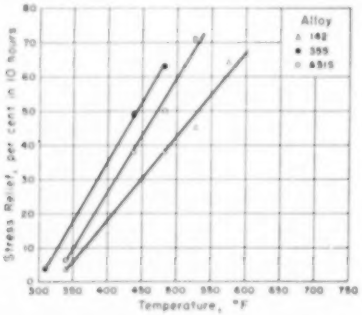

Fig. 23—Effect of reheating temperature on the rate of stress relief in 10 hr of alloy 142, 355, and A51S beam specimens. Beams, 0.25x0.06x12.0 in., were quenched from the commercial heat-treating temperatures into boiling water and stressed 4,000, 7,000, 10,000, and 14,000 psi.

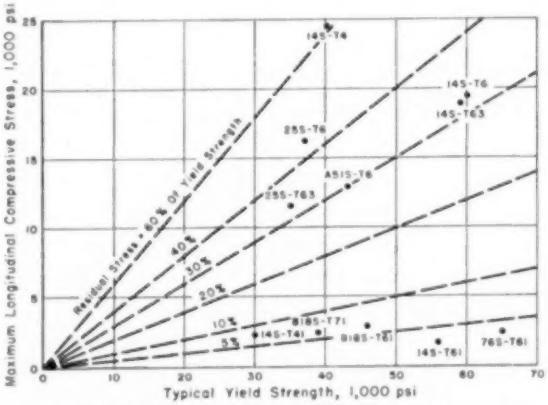

Fig. 24—Relationship of maximum residual longitudinal compressive stress to typical yield strength for aluminum forging alloys in various commercial tempers. Data for 3.0x9.0 in. cylinders.

Residual Stresses in Various Aluminum Alloys With Different Commercial Heat Treatments: The effects of quenching rate, quenching temperature, section size, and alloy composition on the residual stresses resulting from quenching various commercial wrought and cast aluminum alloys have been described. The progressive boring method of Sachs was employed to determine the magnitude and distribution of the stresses. Only a limited number of residual stress determinations were made on cylinders which had been given commercial heat treatments involving aging at elevated temperatures subsequent to quenching because of the expense and time involved in the Sachs method.

It was considered desirable to compile the relative magnitudes of the stresses which could be expected in the various alloys in their respective commercial tempers, the effects of all other factors such as section size remaining constant. Fortunately, cylinders of a standard size were employed for a large proportion of the program. In order to obtain such data, it was necessary to combine the results of the stress determinations on as-quenched cylinders with information on the percentage of stress relief effected by the various aging treatments. The latter information on the rates of stress relief of cast and wrought aluminum alloys was described in the previous section. Rates of stress relief determined by the relaxation beam method were com-

pared with rates measured by the Sachs analysis and found to be identical, Figs. 18 and 21. Thus, the combination of the information obtained by the two experimental methods should provide valid data for determining the stresses present after complete heat treatment.

In some cases results were available for 3.0x9.0 in. cylinders which had been subjected to a commercial heat treatment and artificial aging before stress analysis. Values obtained from such measurements were, of course, valuable and served as a confirmation of the procedure adopted.

The primary objective of this work was to provide data on the comparative residual stresses which

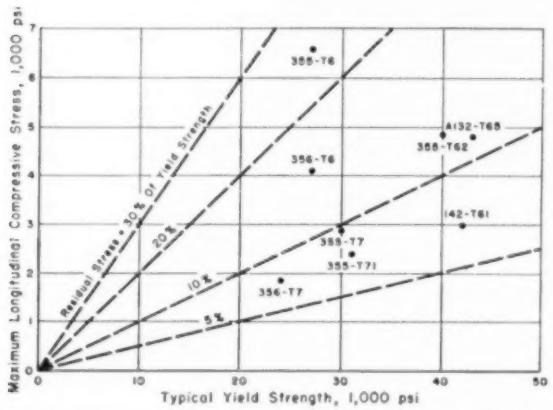

Fig. 25—Relationship of maximum residual longitudinal compressive stress to typical yield strength for aluminum permanent mold alloys in various commercial tempers. Data for 3.0x9.0 in. cylinders.

might prevail in commercial forgings or castings after complete heat treatment. The data revealed differences between alloys as well as between various tempers of a specific alloy. It was apparent from the results that the stresses developed in actual forged or cast parts are affected to a considerable degree by the section size and geometry of the part. However, the results should permit valid conclusions concerning the relative stresses in parts of equivalent size and shape in different alloys and tempers.

Probably the greatest value of such information is its application to the problem of distortion on machining. The character of the stress state, involving triaxial stresses and some variations in the distributions of the three stresses, is so complex that no simple relations have been discovered between the anticipated distortion for a certain machining operation and any of the calculated or measured maximum stress values. However, if a casting or forging of large size were to be bored so that the hole diameter were relatively small in proportion to the external dimensions of the piece, it is probable that the amount of distortion per inch would be approximately proportional to the magnitude of the tensile stresses at the center of the section. The distortion in this case would be expressed by an expansion in the external dimensions. However, if the machining operations removed stock from the surface, the distortion would appear as a contraction, and the relative amount of the contraction would be related to the magnitude and distribution of the surface compressive stresses. Difficulties arising from the release of residual stresses are frequently encountered in slotting. In such operations the magnitude of stresses in both the surface and center layers would be of importance. The commonest manifestation of these changes is the bending or warping of the part.

Maximum longitudinal compressive stresses in various tempers of the forging alloys ranged from 1,600 psi for 14S-T61 to 24,500 psi for 14S-T4, other alloys and tempers investigated having intermediate values. Similar stresses in casting alloys varied from 200 psi for 195-T7 to 6,800 psi for 355-T4. Among the factors affecting the level of residual stresses in heat-treated parts, the quenching rate was indicated to have an influence considerably greater than that of the alloy composition or the elevated temperature aging treatment, and in all cases a heat-treating practice which involved quenching in boiling water produced a much greater reduction in residual stresses than in the tensile properties. Thus, for example, the residual stresses in alloy 14S varied by a ratio of 12 to 1 or more, depending upon whether the quenching water was at 150° or 212°F. Decrease in the magnitude of the residual stresses with elevated temperature aging treatments of the -T6 type varied from 7 to 44 pct among the various forging alloys.

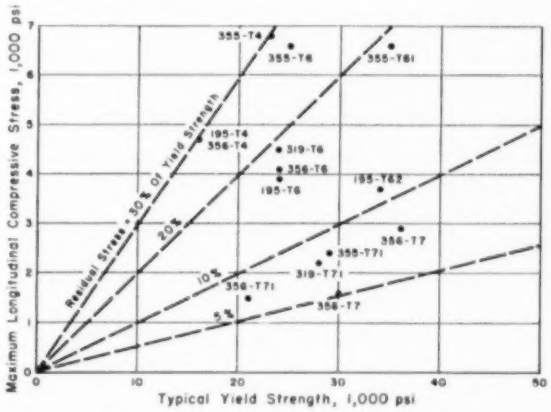

Fig. 26—Relationship of maximum residual longitudinal compressive stress to typical yield strength for aluminum sand casting alloys in various commercial tempers. Data for 3.0x9.0 in. cylinders.

In general, the magnitude of the residual stresses in casting alloys was lower than in forging alloys, because of the prevalence of boiling water quenching for casting alloys. As a result, less variation was encountered among the different casting alloys than among forging alloys in commercial tempers. The percentage of stress relief effected by the elevated temperature aging portions of the -T6 heat treatments varied from 3 pct for casting alloy 355-T6 to 30 pct for 355-T62. The aging cycle of the -T7 type treatments provided stress-relief values of from 43 pct for casting alloy 355-T7 to 96 pct for 195-T7. With the substantial reductions in the magnitude of the residual stresses provided by -T7 type treatments, measurable improvements with respect to distortion on machining can be expected. Generally the most favorable combinations of tensile properties and residual stress values were provided by a low quenching rate followed by artificial aging to the -T6 temper.

Engineers responsible for the design of parts and the selection of suitable alloys and tempers are concerned with relations between the anticipated re-

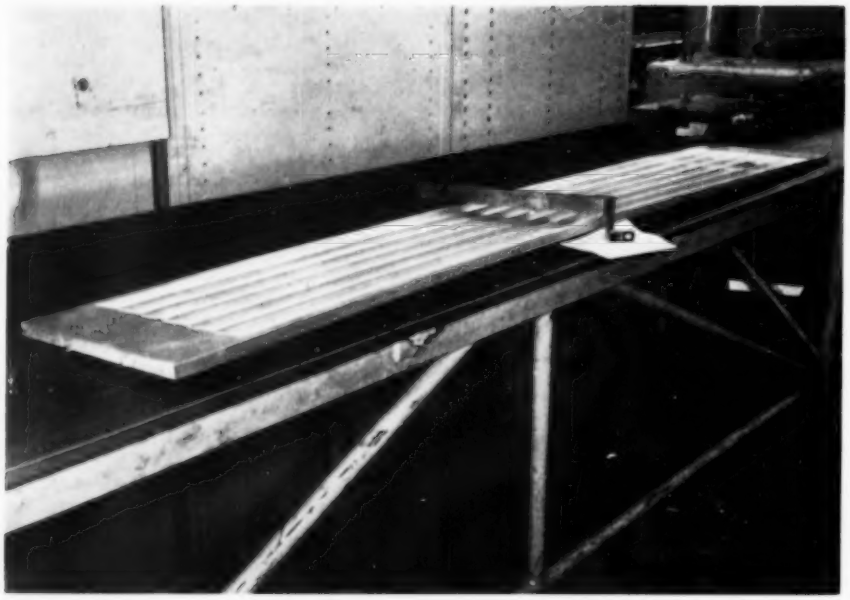

Fig. 27—Machined alloy 75S-T6 test specimen representing the integrally stiffened structure of the Lockheed Super Constellation airplane. Specimen was not stretched after quenching.

sidual surface stresses and the fatigue characteristics of the parts. In some cases the allowable range for fatigue stresses applied in service is restricted by the presence of residual stresses developed in the heat-treating operation.

Consequently, various commercial tempers have been developed for aluminum alloys with the primary objective of fabricating products having a low level of residual stress. These tempers usually do not represent maximum strength properties, but the reduction is modest, considering the degree to which residual stress problems are eliminated. It is, of course, necessary to establish the relation between the typical strength properties of the different tempers of the various alloys and the associated residual stresses. It was decided to express the maximum longitudinal residual compressive stress as a percentage of the typical yield strength. In the case of forging alloys, the longitudinal compressive stress ranged from about 3 pct to as high as 61 pct of the yield strength. This relationship depended not only on the severity of the quench, but also to an appreciable degree on the effects of elevated temperature aging, since a considerable change in yield strength values accompanies the aging treatments.

The relation between the maximum longitudinal residual compressive stress values and the typical yield strengths for the forging alloys is illustrated in Fig. 24. It was apparent that the value of the maximum longitudinal compressive stress in alloys receiving a quench in cold or warm water amounted to 30 to 40 pct of the typical yield strength of the fully hardened temper (-T6 type). When boiling water quenches were employed, the residual stress values were less than 10 pct of the typical yield strengths.

It is of interest that the maximum tangential residual compressive stress was indicated, by the available data from the cast and wrought cylinders, to be approximately equal to the maximum longitudinal compressive stress. Thus, the ratio of the maximum longitudinal compressive stress to the maximum tangential compressive stress varied from 0.79 to 1.21, and the average of this ratio was 0.98. Therefore, the values shown graphically in Fig. 24 can be considered to represent the tangential as well as the longitudinal residual surface stresses. For many purposes the surface longitudinal compressive stresses are undoubtedly the most important; and this consideration, along with the fact that the surface stresses are probably established with greater accuracy and apply to the greatest incremental volume of any cast or forged parts to be machined, was the reason for the selection of the maximum longitudinal compressive stress as providing the most significant data.

The relation of maximum longitudinal residual compressive stresses to the typical yield strengths of various permanent mold casting alloys and tempers is represented in Fig. 25. Similar data for sand casting alloys are presented in Fig. 26.

Relief of Residual Stress by Mechanical Treatments

Mechanical treatments have been used for many years to relieve or realign residual stresses in commercial metal products such as sheet, plate, tube, extrusions, rod, and bar. The mechanical operations employed are stretching, repeated bending, and coining. Stretchers up to 3,000,000 lb capacity, roller levelers, and various other types of roll straightening devices, gag presses, etc. are widely used throughout the metal industry, not only for straightening and forming metal products, but also for reducing the magnitude or improving the distribution of residual stresses in these products. Forgings are often straightened cold in the die.

The mechanism by which the various mechanical treatments reduce residual stresses is perhaps best illustrated by the stretching procedure. Consider a long length of extruded shape in which the outside fibers have a high longitudinal residual compressive stress and the interior layers a correspondingly high longitudinal tensile stress. When the ends of this piece are gripped and the entire piece stretched beyond the elastic range of the alloy, the inner fibers begin to take a permanent set first, because the superimposed tensile stress is added to the residual tension already present. As the stretching force is increased further, the exterior fibers finally begin to assume permanent set, so that the entire cross

section becomes stressed well beyond the limit of elastic action. When the stretching force is removed, both the outer and inner fibers recover nearly the same amount. However, the plastic flow of metal is greater in the interior fibers than in the exterior layers, so that after removal of the stretching force only a small fraction of the initial difference in the residual stresses remains between the inner and outer fibers. One factor controlling the degree of this final difference is the amount of plastic action imposed during the stretching operation. Fortunately, the initial plastic action in such a treatment is more effective than the later stages of plastic flow, so that it is unnecessary to stretch to so high a degree of permanent set that fracture of the piece during the stretching operation might be imminent. Again, fortunately, the amount of stretch required to satisfactorily straighten a part is almost enough to adequately release the residual stresses, and so the minimum required for straightening, or slightly more than this, is the usual amount applied in commercial stretching operations.

The effectiveness of stretching in relieving residual stresses depends also on the uniformity of the mechanical properties, especially yield strength, of the alloy product being stretched. If the cross section is not initially uniform in mechanical properties, stretching can actually produce residual stresses in an otherwise stress-free piece. Of course, the stresses so formed are usually of a smaller magnitude than those produced by quenching in cold water, so that the net effect of stretching is beneficial, even though some minor differences exist in mechanical properties across the cross section. Nevertheless the maximum benefits in relieving residual stresses by stretching can be attained only in a material which has substantially uniform mechanical properties across the cross section.

Tests have repeatedly demonstrated the beneficial effect of stretching on the relief of residual stresses. In one investigation, for example, 75S-T6 extruded shapes after stretching showed only 10 pct as much warping on machining as was characteristic before stretching. In another test, illustrated in Fig. 27, a 75S-T6 specimen representing the integrally stiffened structure on the Lockheed Super Constellation was machined without having been stretched after quenching. The distortion of the specimen is apparent on the inspection surface plate. In contrast, Fig. 28 reveals the flatness of a similar machined specimen that was stretched between quenching and artificial aging.

Stretching operations are used commercially today on many aluminum alloy products covering a wide range of sizes. Spar chords for airplanes provide another example of aluminum alloy products straightened by stretching after heat treatment that show greatly reduced warpage on machining because the residual stresses have been largely eliminated. Airplane spar chord sections with a cross section of 60 sq in. can be successfully stretched. Very satisfactory results both as to straightness and freedom from warpage on machining have been obtained by such mechanical treatments in many commercial applications.

Relief of Residual Stresses by Combinations Of Thermal and Mechanical Treatments

Mechanical treatments followed by a thermal stress relief are frequently employed to obtain the desired combination of mechanical properties and reduction in residual stresses. An example is the flattening procedure applied to magnesium-base alloy sheet, where a combination of dead load and thermal treatment was used to produce flat, stress-free sheet. Another application is the relatively new method being used by North American Aviation Co. for simultaneously forming, quenching, and stretching high strength aluminum alloy parts by a die quenching process.

Closure

Two objectives have been reached in this exploration of the field of residual stresses in metals. Both the beneficial and the injurious effects of these

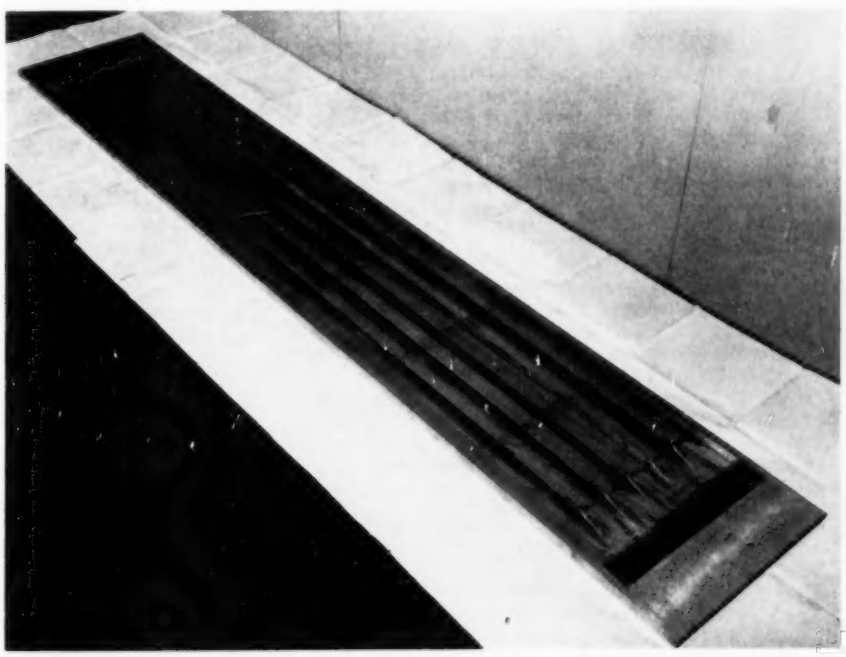

Fig. 28—Machined alloy 75S-T6 test specimen representing the integrally stiffened structure of the Lockheed Super Constellation airplane. Specimen was stretched after quenching but before artificial aging.

stresses have been presented in a qualitative and quantitative manner. Numerous examples from commercial experience illustrate the location of these residual stresses and the practical effects which they introduce. Much experimental work remains to be done in this field, however, and it is hoped that this report will provide a useful background of information which will stimulate others to acquire more of the fundamental knowledge necessary for the control of these forces.

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Tristage Crystallization Process For Utilizing Western Ferrophosphorus

by Lloyd H. Banning, Wallace E. Anable, and R. T. C. Rasmussen

In the rapidly growing industry of elemental-phosphorus production from western phosphates, most of the vanadium and chromium contained in the phosphate rock collect in the byproduct ferrophosphorus. Results are presented of a completed laboratory project, which developed a tristage crystallization and hydrolysis process for recovering strategic vanadium and chromium, as well as a valuable phosphorus product, after extracting these elements from the ferrophosphorus by roasting and leaching.

THE Phosphoria formation in Idaho, Montana, Wyoming, and Utah contains the Nation's largest reserve of phosphate rock. A unique feature of the Phosphoria beds is their content of a fraction of a percentage each of vanadium, chromium, nickel, and molybdenum. Vanadium is the most important as to quantity and value.

Small-scale tests by the Bureau of Mines at Albany, Oregon, in 1947, indicated that most of the vanadium in the phosphate rock collects in the ferrophosphorus product of smelting. Subsequent electric smelting operations to produce elemental phosphorus from western phosphate rock (experimentally by TVA and industrially at Pocatello, Idaho) have shown that the vanadium and other metals in the rock are to a large extent recovered in concentrated form in the ferrophosphorus byproduct.

This paper reports the results of completed laboratory research on the recovery of vanadium from ferrophosphorus, which was undertaken by the Bureau of Mines at Albany in 1948 as the first phase of a project entitled, "Vanadium and Fluorine from Western Phosphates." The various vanadium-recovery methods investigated, including the roast-leach method that showed most promise and was studied in greatest detail, are discussed in an earlier publication.[1] Subsequent systematic study of the roast-leach method of extracting vanadium from western ferrophosphorus developed the more efficient tristage crystallization process, which is the subject of this paper.

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Table I. Test Lots of Western Ferrophosphorus

Lot	Analysis, Pct				
	V	P	Fe	Cr	Ni
TVA 1	3.26	26.6	60.8	3.4	0.84
TVA 2	3.85	26.0	59.9	4.0	0.95
Westvaco A	4.0	25.9	60.7	5.7	0.98
Westvaco B	5.2	24.7	58.5	5.2	1.0

Process Development

The investigations were made on ferrophosphorus produced in the electric smelting of elemental phosphorus from western phosphate rock. The TVA provided two sample lots of ferrophosphorus produced in pilot plant smelting of phosphatic shale from the Fort Hall Indian Reservation in Idaho. The Westvaco Chemical Div. of the Food Machinery & Chemical Corp. supplied two sample lots of ferrophosphorus produced by its phosphorus smelter at Pocatello, Idaho. The analyses of all four lots are shown in Table I. Westvaco lot B was the starting material for the more recent tests.

The roast-leach process for recovering vanadium from western ferrophosphorus, as originally developed, employed the following principal steps: Roasting of a mixture of pulverized ferrophosphorus, soda ash, and salt; extraction of the water-soluble vanadium, phosphorus, and chromium compounds from the calcine by leaching, settling, and decantation of the pregnant solution; primary crystallization of trisodium phosphate from the pregnant solution; purification of the trisodium phosphate crystals by dissolution in water and secondary crystallization; purification of the pregnant vanadium solution from the primary crystallization step by adding calcium chloride to precipitate calcium phosphate; and hydrolysis of vanadium red cake from the puri-

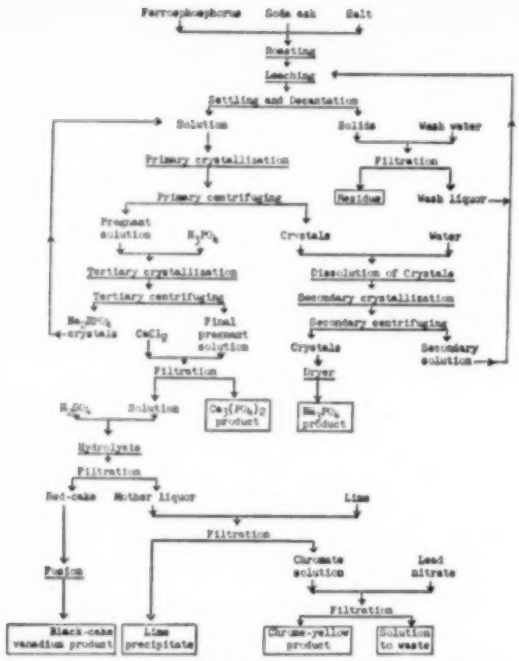

Fig. 1—Flowsheet of tristage crystallization process for recovering vanadium, phosphorus, and chromium products from western ferrophosphorus.

fied pregnant solution. It was recognized that more detailed and systematic study of the several unit operations was desirable, particularly with respect to making a more complete separation of phosphorus from vanadium-bearing solution by crystallization. Methods of recovering chromium remaining in solution after hydrolyzing vanadium also needed to be investigated.

The tristage crystallization process developed in subsequent research is illustrated by the flowsheet of Fig. 1. It differs from the original roast-leach process principally by the addition of a tertiary crystallization step to remove much of the phosphorus remaining in the pregnant vanadium solution from the primary crystallization step. Instead of crystallizing trisodium phosphate, as in the primary and secondary crystallizations, disodium phosphate is brought down by addition of phosphoric acid to the solution before cooling for the tertiary crystallization. This step brings the phosphorus content of the pregnant vanadium solution to a much lower figure than was previously obtainable and also permits recovery of a larger proportion of the phosphorus in a high-purity sodium phosphate product.

As shown on the flowsheet, the more recent studies included tests on conversion of the red-cake product to black-cake and developed one method of recovering chromium as a marketable compound. A more detailed study also was made of the controlling variables in other steps of the process.

Each of the several unit operations comprising the tristage crystallization process will be described individually.

Roasting of Ferrophosphorus with Soda Ash and Salt: The object of roasting is to oxidize the metallic ferrophosphorus and form water-soluble vanadium, phosphorus, and chromium compounds, while avoiding formation of soluble iron compounds. Roasting variables investigated were: soda ash-ferrophosphorus ratio, salt-ferrophosphorus ratio, fineness of the ferrophosphorus, temperature, time, degree of oxidation, and amount of rabbling. Most of the roasting tests were carried out in a small rotary kiln.

The optimum quantity of soda ash in the roasting charge was found to be approximately the sum of the quantities theoretically required to react with phosphorus to form trisodium phosphate (Na_3PO_4), with vanadium to form sodium metavanadate ($NaVO_3$), and with chromium to form sodium chromate (Na_2CrO_4). A satisfactory ratio of dry soda ash to Westvaco ferrophosphorus was 1.45:1. A small quantity of salt (NaCl) in the roasting charge was beneficial, but an excess of salt caused the charge to become plastic below the optimum roasting temperature and resulted in mechanical difficulties. One part of salt to 10 parts of Westvaco ferrophosphorus gave satisfactory results.

Grinding of the ferrophosphorus to −35-mesh provided roaster feed of optimum particle size. Finer grinding accelerated the roasting reaction but increased dust losses, whereas coarser grinding resulted in a less soluble calcine.

The related roasting variables of temperature, time, degree of oxidation, and amount of rabbling must be balanced to obtain calcine having good leaching characteristics, and their control depends to a large extent upon the type of roaster employed. The preferred maximum roasting temperature in the small rotary kiln was between 780° and 800°C. At higher temperatures the charge became plastic, resulting in the formation of nodules that were not properly calcined throughout. The best leach extractions were obtained from calcine that was in the hot zone of the furnace for about 2 hr. Enough oxidation must be attained to produce pentavalent vanadium and phosphorus and hexavalent chromium. Excessive oxidation apparently produces water-soluble sodium ferrate, which causes difficulties in subsequent leaching and crystallization. The degree of oxidation is a function of the roaster atmosphere and of gas-solids contact produced by rabbling, or by tumbling in the rotary kiln, for a given time at roasting temperature.

The best combination of roasting conditions attained in the rotary kiln tests produced calcine in which 95 pct each of the vanadium and phosphorus, 70 pct of the chromium, and virtually none of the iron in the ferrophosphorus were rendered water-soluble.

Leaching of Calcine and Separation of Dissolved Values from Residue: In the early batch leaching tests 500 g of calcine was ground for 5 min in a laboratory ball mill with 2 liters of secondary solution from a previous test. The ground pulp was transferred to a leaching vessel and gently boiled with agitation for 1 hr. After leaching, the solids were settled at a temperature high enough to prevent crystallization. The solution usually was clear enough to decant after settling for 3 hr. The decanted primary solution was sent to the primary crystallization step, while the solids were repulped with water, releached, filtered, washed, dried, and sampled for analysis. The filtrate and washings were combined with the secondary solution from the secondary crystallization step of the process for use in leaching the next batch of calcine.

Later investigations revealed that it was not necessary to grind the calcine before leaching. The procedure subsequently used in simultaneous roasting and leaching tests was to discharge calcine from

the kiln directly into a vigorously agitated boiling leach solution. The specific gravity of the pulp in the leaching vessel was adjusted by frequent small additions of water and recycled solution. When the leaching vessel became full, part of the pulp was removed and filtered.

Occasionally iron was present in the clarified leach solutions in high enough concentration to precipitate during crystallization and discolor the sodium phosphate product. Furthermore, high iron concentration appeared to retard crystallization. The clarified leach solution was acceptably low in iron when the following conditions were met: The solution was alkaline enough so that trisodium phosphate crystals formed on cooling, the pulp was kept vigorously boiling during the leaching operation, the specific gravity of the pulp was kept below 1.27, and the calcine was leached for at least 1 hr.

The leach pulp was kept above the crystallization temperature of trisodium phosphate, which is a function of the phosphorus concentration, until the solution and solids were separated. No trouble was experienced with sodium phosphate crystallizing from solution when the temperature was maintained above 60°C.

Primary Crystallization and Centrifuging: In the primary crystallization and centrifuging operations trisodium phosphate is crystallized and separated from the pregnant solution. The purpose of the step is to make the optimum separation of phosphorus from vanadium and chromium; complete separation cannot be attained as the trisodium phosphate crystals include small amounts of vanadium and chromium, and the remaining solution contains some phosphorus. In the development work on the process a study was made of the relationship between vanadium and phosphorus content of solution and temperature of crystallization. A typical 1500 milliliter sample of primary solution, analyzing 12.1 g V and 54.0 g P per liter, was cooled in the laboratory crystallizer to 20°C and held at this temperature 30 min. A sample of the mother liquor was then drawn from the crystallizer through a submerged fritted glass filter and analyzed for phosphorus and vanadium. The same procedure was repeated for the following temperatures: 15°, 12°, 9°, 6°, 3°, and −3°C. The vanadium and phosphorus analyses and the ratios of vanadium to phosphorus of the mother liquor after each crystallization are shown in Table II.

Results of the crystallization studies indicate that the optimum crystallization temperature for a primary solution containing 12 g of vanadium per liter is between 3° and 6°C, as the vanadium-phosphorus ratio is highest in this temperature range. The relationship between vanadium and phosphorus content of pregnant solution and temperature of crystallization is shown graphically in Fig. 2. It is evident from the graph that the phosphorus content of pregnant solutions decreases linearly as the crystallization temperature is lowered. Conversely, the vanadium content increases to a maximum at about 6°C, then rapidly decreases at lower temperatures. These studies indicate that, if the primary solution were higher in vanadium, the optimum crystallization temperature would be higher, as sodium vanadate would start crystallizing from solution at higher temperature. On the other hand, if the vanadium content were lower, the optimum crystallization temperature would be lower. Hence, the optimum crystallization temperature for a primary solution of known vanadium concentration can be estimated from these data.

Table II. Effect of Primary Crystallization Temperature on Vanadium and Phosphorus Content of Pregnant Solution

Temperature, °C	Analysis, G per Liter		V-P Ratio
	V	P	
60	12.1	54.0	0.22
20	16.1	9.5	1.7
15	17.1	8.0	2.14
12	17.7	7.6	2.32
9	17.5	6.1	2.87
6	18.1	5.9	3.06
3	17.5	4.4	3.98
0	11.1	4.1	2.70
−3	7.6	2.8	2.50

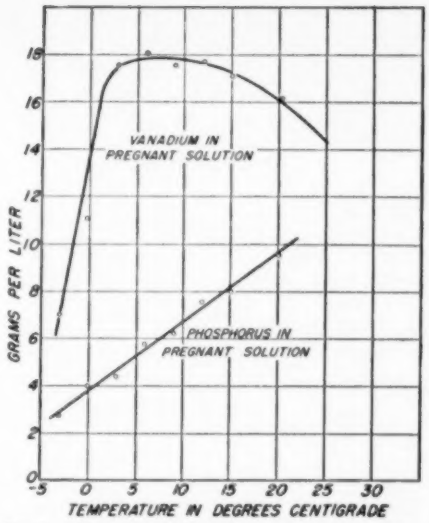

Fig. 2—Effect of crystallization temperature on vanadium and phosphorus content of pregnant solution.

Centrifuging has proved superior to filtration for separating crystals from solution, mainly because a drier crystal product can be recovered. In some of the early tests using filtration, the crystals always contained appreciable percentages of vanadium and chromium. By centrifuging, a drier crystal product low in vanadium and chromium was recovered.

Optimum separation of crystals from solution by centrifuging is made only when the minimum crystallization temperature is maintained until the separation is complete. The procedure used in the laboratory test work was to cool the 12-in. basket of the suspended-type centrifuge with ice water before introduction of the crystal-solution mixture. With the basket loaded, the centrifuge was raised to a speed of 3000 rpm. After spinning for 2 min, the crystals were washed with a small amount of ice water, then spun dry in about 1 min.

Purification of Trisodium Phosphate Crystals by Secondary Crystallization: The vanadium and chromium contents of the primary trisodium phosphate crystals vary from 0.1 to 0.2 pct, and the crystals are slightly yellow. To produce a commercial grade of trisodium phosphate the primary crystals must be freed of vanadium and chromium by dissolution in water and recrystallization. Therefore, studies were made to determine optimum conditions for the recrystallization procedure.

A series of eight secondary crystallization tests indicated that a linear relationship exists between

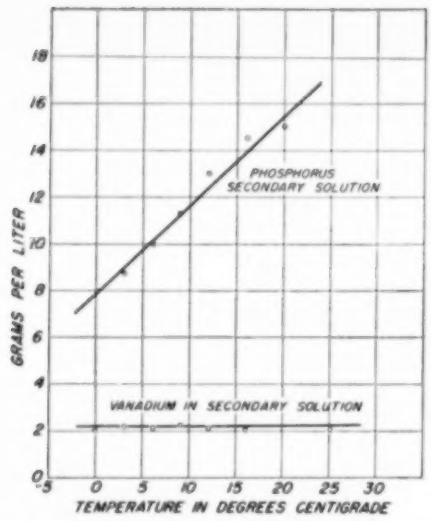

Fig. 3—Effect of crystallization temperature on vanadium and phosphorus content of secondary solution.

the minimum crystallization temperature and the phosphorus content of the secondary solution. The vanadium content of the crystals did not increase at lower crystallization temperatures, as it did in the primary crystallization step. The results of these tests, shown graphically in Fig. 3, indicate that the optimum crystallization temperature is just above the freezing point of the solution.

The effect of phosphorus concentration of solution on the purity of the trisodium phosphate product was investigated in eight recrystallization tests. Solutions with phosphorus concentrations ranging from 27 to 68 g per liter were prepared by dissolving wet primary crystals that contained 0.09 pct V and 6.2 pct P in water. The tests were conducted by cooling 1500 milliliter batches to −1°C and holding at this temperature for 30 min before centrifuging. The crystal products and solutions were measured and analyzed for vanadium and phosphorus. The result of these tests is shown graphically in Fig. 4.

A study of the results of the secondary crystallization tests indicates that under specific conditions a tenfold reduction of the vanadium content of primary crystals can be obtained while recovering 88 pct of the phosphorus in the purified trisodium phosphate crystals and 91 pct of the vanadium in the secondary solution. The graphs also indicate that a choice must be made between high crystal yield and low vanadium content of trisodium phosphate crystals in the secondary crystallization operation. However, low crystal yield in this operation does not necessarily mean low overall phosphorus recovery as the secondary solution is recycled to the leach tank. Only the phosphorus in the residue and in the purified pregnant solution is lost. In plant practice it should be possible to obtain a high overall recovery of phosphorus as trisodium phosphate crystals of low vanadium content.

Purification of Pregnant Solution: When the optimum vanadium-phosphorus separation is made in the primary crystallization and centrifuging operations, the phosphorus content of the pregnant solution is 6 to 8 g per liter. The solution for the vanadium hydrolysis operation must contain no more than about 1 g of phosphorus per liter in order to get a satisfactory recovery of vanadium as red cake of acceptably low phosphorus content. The conventional procedure for reducing the phosphorus content of pregnant solution is to neutralize with acid and add sufficient calcium ion to precipitate phosphorus as calcium phosphate. The precipitate invariably contains appreciable vanadium and, hence, the more phosphorus that is precipitated from solution as calcium phosphate the lower is the vanadium recovery.

Investigations revealed that disodium phosphate could be crystallized from pregnant solution to the extent that less than 1 g per liter of phosphorus remained in solution. Disodium phosphate was crystallized from pregnant solution by adjusting the pH to 8.8 with phosphoric acid before cooling. Tests have shown that phosphoric acid is the most desirable reagent for the pH adjustment, as the use of other acids introduces foreign ions into the solution which show up in crystals and contaminate the final

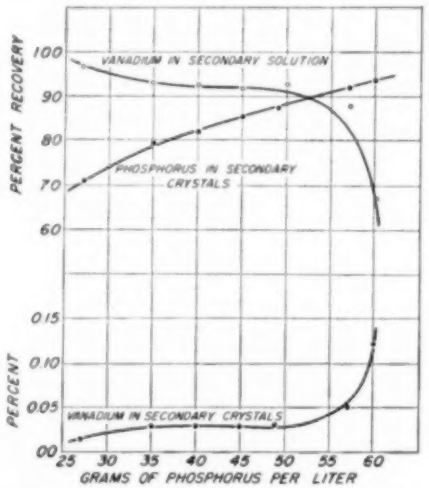

Fig. 4—Effect of dilution on the purification of primary crystals.

trisodium phosphate product. To determine the relationship between temperature of crystallization and phosphorus content of pregnant solution, a series of eight tests was made, the results of which are shown graphically in Fig. 5.

When the third crystallization and centrifuging operation is carried out under favorable conditions, the resulting solution may be used directly for hydrolysis. The crystals from these operations are dissolved in the clarified solution from the primary leaching step; and the phosphorus, including that added as phosphoric acid, is recovered in the trisodium phosphate product. If a higher purity vanadium red-cake product is desired, the solution can be further freed of phosphorus by precipitation with calcium ion before hydrolysis.

Recovery of Vanadium by Hydrolysis: Vanadium recovered from ores is usually sold as fused black vanadium oxide. For grade A fused black vanadium oxide (suitable for manufacture of ferrovanadium and special alloys, direct addition to alloy steel, or the manufacturing vanadium chemicals) the Army and Navy Munitions Board specifies a minimum of 86 pct V_2O_5 (48.2 pct V) and a maximum, in percent, of: P, 0.05; S, 0.15; Cu, 0.05; Sb, 0.05; As, 0.05; Ni, 0.10; Pb, 0.15; Zn, 0.15; and insolubles, 1.0. When recovering vanadium from ores, phosphorus is probably the most troublesome impurity to eliminate

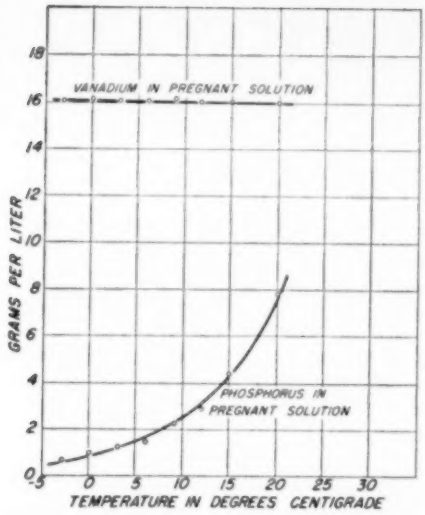

Fig. 5—Temperature relationships when crystallizing disodium phosphate.

from the final vanadium product. The ferrophosphorus used in the test work contained from 4 to 5 pct V and 24 to 25 pct P; so the problem of separating phosphorus from the vanadium product was particularly difficult. By the three crystallization and centrifuging operations described in the foregoing, the vanadium-phosphorus ratio was raised to 15 to 1 in the final pregnant solution, and in some tests the pregnant solution contained as little as 1 g of phosphorus per liter. Still more of the phosphorus can be eliminated from solution prior to hydrolysis by neutralization with sulphuric acid and precipitation of phosphorus as calcium phosphate, thereby increasing the vanadium-phosphorus ratio to as high as 60:1. The final separation of vanadium from phosphorus takes place in the hydrolysis operation.

The apparatus in which hydrolysis tests were first successfully carried out consisted of a 3-neck, 1-liter flask, equipped with a reflux condenser, a thermometer, a mechanical stirrer, and a constant level water bath. Later, to simulate plant conditions more closely, a 3-liter stainless steel beaker was substituted for the 3-neck glass flask. Then, in some of the last tests, a 7-liter stainless steel beaker was used. Equally satisfactory recoveries and grades of red-cake product were obtained in the stainless steel beakers as in the all-glass apparatus.

In making the hydrolysis tests, the pH of the solution was adjusted, after which the solution was heated to the desired temperature while being agitated. In most of the tests the solution was heated to the boiling point, and the volume of solution was kept constant by condensing the vapors and returning them to the hydrolysis vessel or by the addition of water. Samples of the solution were checked at frequent intervals for pH and for vanadium content.

Table III. Results of Some Hydrolysis Tests

Test No.	Red-Cake Analysis, Pct			V Yield, Pct
	V	P	Cr	
17	45.4	0.01	0.7	96.2
18	43.8	0.01	1.1	96.1
19	42.4	0.01	0.8	84.4
20	42.9	0.22	0.8	92.8

Note: Spectrographic analysis of red cakes from tests 18 and 20 indicated no impurities over specifications.

Although the hydrolysis of vanadium from solution is a known procedure, some variables of the hydrolysis operation were given careful study. These studies indicated the following trends:

1—The rate of the hydrolysis reaction and the percentage yield are dependent upon the vanadium concentration of the solution.

2—High phosphorus concentration in the hydrolysis solution depresses the reaction rate, lowers the yield, and contaminates the red-cake product.

3—The hydrolysis reaction rate is accelerated by raising the temperature.

4—Small acid additions at intervals of 15 min until the pH is stabilized accelerate the reaction rate.

The manner in which some of the foregoing trends were determined may be graphically illustrated. To study the effect of hydrogen ion concentration (pH)

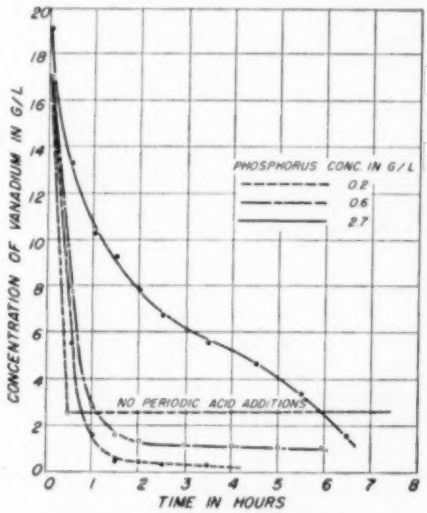

Fig. 6—Hydrolysis of vanadium solutions.

on hydrolysis rate, two tests were made on identical pregnant solutions containing only 0.2 g of phosphorus per liter. In one test (No. 18), after the initial adjustment of the pH to 3.0, 2 milliliter additions of sulphuric acid were made at 15-min intervals. Thirty minutes after the test was started the pH of the solution had increased to 4.6, but after 2 hr it had dropped to 3.1 and the acid additions were stopped. In another test (No. 19), no acid additions were made after the initial adjustment of the pH to 3.0. After a half hour of operation the pH of the solution had increased to 4.9 and precipitation of vanadium apparently ceased. The results of these tests are plotted in Fig. 6. To illustrate the effect of phosphorus concentration in the solution on the rate and completeness of vanadium yield, the results of tests 17 and 20 are also plotted in Fig. 6. In these tests small acid additions were made frequently as described for test 18. The phosphorus content of the solution in test 17 was 0.6 g per liter, and in test 20, 2.7 g per liter. The analyses of the red-cake products from these tests are shown in Table III.

Red cake is a light, fluffy precipitate, and for most commercial uses fused black vanadium oxide is preferred. Red cake is converted to the fused black form by heating to 800°C and then tapping into a suitable mold. Laboratory tests have indicated that the fused black vanadium oxide is higher in vanadium and lower in phosphorus than the red cake from which it was produced. In a typical test the vanadium

content increased from 45.1 pct in the red cake to 47.9 pct in the black cake and the phosphorus content dropped from 0.15 to 0.029 pct. In another test the vanadium content increased from 41.8 pct in the red cake to 50.2 pct in the black cake. Spectrographic as well as chemical analyses indicated no objectionable quantities of undesirable impurities in the fused, black-cake products.

Recovery of Chromium: After recovery of phosphorus as trisodium phosphate and vanadium as red cake, almost all of the chromium leached from the calcine remains in solution at a concentration of 10 to 14 g per liter. The most promising method investigated for recovering chromium from this solution was precipitation as chrome yellow (lead chromate). The object of the investigation was to determine whether pigment-quality chrome yellow could be recovered. The composition requirements for commercially pure lead chromate pigments, according to the ASTM Specification D211-47, are shown in Table IV.

Before pigment-quality chrome yellow could be recovered from the vanadium hydrolysis filtrate, it was necessary to free the solution of 0.02 to 2.0 g of phosphorus per liter, 0.25 to 1.0 g of vanadium per liter, and some of the excess sulphate radical.

Table IV. Requirements for Composition, Chrome Yellow and Chrome Orange

	Type				
	I	II	III	IV	V
Lead chromate ($PbCrO_4$) minimum, pct	50	68	93	60	55
Total matter soluble in water, maximum, pct	1.0	1.0	1.0	1.0	1.0
Total of all substances other than insoluble compounds of lead, maximum, pct	8.0	8.0	7.0	3.0	3.0
Moisture and other volatile matter, maximum, pct	1.0	1.0	1.0	1.0	1.0
Coarse particles, total residue retained on a No. 325 (44-micron) sieve, maximum, pct	1.0	1.0	1.0	1.0	1.0

Lime was used to precipitate these impurities. Upon the addition of lime, phosphorus precipitated first; when enough lime was added to raise the pH of the solution to 10.9, vanadium precipitated. Lime added in excess of that required to precipitate phosphorus and vanadium precipitated the sulphate radical. Part of the sulphate in the solution resulting from the hydrolysis of vanadium may be used to good advantage in the chrome yellow, as it precipitates as insoluble lead sulphate.

The main constituent of the lime precipitation product was calcium sulphate. Tests have indicated that less than 4 pct of the chromium was lost in this product and that excess lime caused no additional loss of chromium.

After the solution was freed of phosphorus, vanadium, and excess sulphate radical, chromium was precipitated as chrome yellow with lead nitrate or lead acetate. The effects of varying lime and lead acetate additions were demonstrated in a series of tests. In some, the lime used to precipitate impurities from solution was varied from 12.5 to 25 g per liter and the theoretical amount of lead acetate was used for precipitating chrome yellow. In others, the lime additions were held constant at 12.5 g per liter and the lead acetate additions were varied from 50 to 150 pct of the theoretical. In still others, the lime additions were held constant at 25 g per liter and the lead acetate additions varied the same as in the second series.

Table V. Chromium Recovery from Purified Hydrolysis Filtrate

Chromium, G per Liter	Lime Used, G per Liter	$Pb(Ac)_2$ Used, G per Liter	Chrome Yellow Recovered, G	Chromium Recovery, Pct	Chrome-Yellow Product, Analysis, Pct	
					$PbCrO_4$	$PbSO_4$
9.85	12.5	30.7	36.5	58.6	101.9	Nil
9.56	25.0	29.9	37.0	54.6	93.8	Nil
9.85	12.5	46.1	66.0	86.5	95.7	2.3
9.56	25.0	44.8	52.0	80.2	101.9	Nil
9.85	12.5	61.5	76.5	97.5	93.2	4.5
9.85	16.7	61.5	77.5	97.5	93.8	2.5
9.85	20.8	61.5	74.0	99.4	93.2	1.2
9.56	25.0	59.8	76.5	98.1	95.7	1.9
9.85	12.5	76.9	84.0	98.9	81.4	16.5
9.56	25.0	74.8	79.0	98.3	87.6	15.6
9.85	12.5	92.2	96.0	98.9	63.4	31.1
9.56	25.0	89.7	93.0	99.5	70.8	22.4

It was assumed that all of the chromium in the chrome yellow precipitate was present as $PbCrO_4$ and that all of the sulphur was present as $CaSO_4$. In some tests, the calculated lead chromate added up to over 100 pct. In others the calculated lead chromate plus the calculated calcium sulphate added up to over 100 pct. These results indicate that the assumption as to compounds present may not be altogether correct. Nevertheless, this series of tests shows that, by proper lime control in the precipitation of impurities and subsequent controlled lead acetate additions, it may be possible to produce any type of pigment-quality chrome yellow from the chromium in the hydrolysis filtrate. The results of these tests are shown in Table V.

Simulated Plant Test

The object of this test was to simulate plant operating conditions and to determine the recovery of vanadium, phosphorus, and chromium in finished products under such conditions. The first step in the process, roasting, was done in a small rotary kiln of 8-ft length and 5-in. ID. The kiln was set on a slope of ½ in. per ft and rotated 1¼ rpm. Temperature in the kiln was automatically controlled between 1430° and 1450°F.

The charge for the test was a mixture of 18 lb of −35-mesh ferrophosphorus, 26.1 lb of soda ash, and 1.8 lb of salt (NaCl). The mixed charge was fed continuously to the kiln. After normal operating conditions were established, the calcine was discharged into agitated pulp in a leaching vessel. The specific gravity of the pulp was maintained between 1.25 and 1.30 by frequent water and solution additions. Heat was applied to the leaching vessel to keep the pulp boiling. When the leaching vessel became full, part of the pulp was removed, filtered, and the filter cake washed with water. The filter cake was then repulped with water and releached. During the two-day operation, seven batches of pulp were processed. The results of the leaching operation are shown in Table VI, and a materials balance for the roasting and leaching operations is shown in Table VII.

Table VI. Results of Continuous Leaching of Calcine

	G or Milliliter	Analysis, Pct or G per Liter			Distribution, Pct		
		V	P	Cr	V	P	Cr
Primary solution	29,840	8.17	41.0	6.69	88.3	90.2	71.7
Washings	5,970	2.69	8.6	0.93	5.8	3.8	2.0
Releach solution	4,620	1.02	4.1	0.50	1.7	1.4	0.8
Residue	4,508	0.25	1.4	1.57	4.2	4.6	25.5

The materials balance indicates that 98.1 pct of the vanadium, 96.0 pct of the phosphorus, and 100 pct of the chromium contained in the materials that went into the test were accounted for in the products. The retention of vanadium, phosphorus, and chromium in the combined kiln and dust-box clean out was high, as the calcine that was discharged from the kiln before normal operating conditions were reached was included in this product. Under continuous operating conditions this loss would be almost negligible. Disregarding the loss in the combined kiln and dust-box clean out, 94.5 pct of the vanadium, 93.9 pct of the phosphorus, and 69.3 pct of the chromium were extracted from the ferrophosphorus. The primary solution contained 91.1 pct of the extracted vanadium, 93.2 pct of the extracted phosphorus, and 95.0 pct of the extracted chromium.

The primary crystallization operation was carried out by cooling 1600 milliliter batches of primary solution to 5°C in a laboratory crystallizer. Four batches were crystallized and stored in a refrigerator, then combined before centrifuging. Four batch centrifuging operations were required to treat all of the crystallized product. The crystal-solution mixtures were introduced into the centrifuge at temperatures of from 4° to 6°C. The pregnant solution warmed to about 10°C in the centrifuging operation. The results of the individual centrifuging tests and the calculated composite results of the tests are shown in Table VIII.

Table VII. Materials Balance for Roasting and Leaching Operations

Product	G or Milliliter	Analysis, Pct or G per Liter V	P	Cr	G V	P	Cr
To Process							
Ferrophosphorus	8,161	5.2	24.7	5.2	424.4	2016	424.4
Solution 1	6,000	4.67	27.0	4.25	28	162	25.5
Solution 2	6,000	4.06	27.0	3.70	24.4	162	22.2
Total to process					476.8	2340	472.1
From Process							
Kiln and dust-box clean-out	9,456	2.01	9.4	2.05	192.0	889	193.8
Combined residues	4,508	0.254	1.4	1.57	11.4	63.1	70.8
Primary solution	29,840	8.17	41.0	6.69	243.8	1223	199.6
Filter washings	5,975	2.69	8.6	0.93	16.1	51.4	5.6
Releach solution	4,620	1.02	4.1	0.50	4.7	18.9	2.3
Total from process					468.0	2245.4	472.1

The primary crystals contained 8.15 pct of the vanadium, 85.18 pct of the phosphorus, and 11.22 pct of the chromium present in the primary solution. To free the primary crystals of vanadium and chromium the crystals were dissolved in water, trisodium phosphate was crystallized from the solution, and the crystals separated from solution by centrifuging. Three series of crystallization and centrifuging tests were required to handle all of the solution. The phosphorus content of the solution to the first series of crystallization tests was 54 g per liter, but in the last two series the phosphorus content was adjusted to 45 g per liter. In each 1600 milliliter batch crystallization run the batch was cooled to −1°C and then stored in the refrigerator until the four batches required for the centrifuging test had accumulated. In the first centrifuging test the crystal-solution mixture was introduced into the centrifuge at 4°C, and secondary solution discharged from the centrifuge at 11°C. The crystals were washed in the centrifuge with 200 milliliters of ice water. In the second centrifuging test the crystal-solution mixture was introduced into the centrifuge at 1°C and the secondary solution discharged at 9°C. The conditions for the third centrifuging test were the same as for the second.

Table VIII. Results of Primary Crystallization and Centrifuging Tests

Test	Product	G or Milliliter	Pct or G per Liter V	P	Cr	Distribution, Pct V	P	Cr
1	Crystals	4,199	0.13	5.5	0.07	8.62	83.68	8.13
	Solution	5,360	10.8	8.4	6.2	91.38	16.32	91.87
2	Crystals	3,379	0.16	6.8	0.19	9.46	85.80	14.75
	Solution	4,580	11.3	8.3	8.1	90.54	14.20	85.25
3	Crystals	3,379	0.14	6.9	0.09	8.72	86.41	7.92
	Solution	4,420	11.2	8.3	8.0	91.28	13.59	92.08
4	Crystals	1,391	0.05	5.5	0.21	3.15	84.25	15.77
	Solution	1,880	11.4	7.6	8.3	96.85	15.75	84.23
Composite	Crystals	13,348	0.13	6.24	0.12	8.15	85.18	11.22
	Solution	16,240	11.1	8.2	7.5	91.85	15.82	88.78

The crystal product from this step in the process is the final trisodium phosphate product, and in this test it contained 1.08 pct of the vanadium from the primary solution. Chemical analysis of a sample of the dried crystal product showed a phosphorus content of 18.3 pct. The results of the secondary crystallization tests are shown in Table IX.

Assuming that all of the phosphorus extracted from the calcine is recovered in the form of trisodium phosphate except that lost in the final pregnant solution, the calculated phosphorus recovery for this test is 91.7 pct.

Perhaps the most noteworthy feature of this process is the addition of phosphoric acid to the pregnant solution from the primary crystallization step so that the solution can be freed of about 90 pct of its phosphorus by crystallization. For every gram of vanadium in the pregnant solution there was 0.74 g of phosphorus. Phosphoric acid was added to the pregnant solution to adjust the pH to 8.8 so that disodium phosphate would crystallize from solution on cooling. In this test the phosphoric acid addition amounted to approximately ½ g of phosphorus per gram of contained vanadium. After the tertiary crystallization and centrifuging operations, the vanadium-phosphorus ratio in the final pregnant solution was 1:0.078.

The adjusted solution was crystallized and centrifuged in the same manner as previously, with three centrifuging tests, each on the combined product of four 1600 milliliter batch crystallization runs. The crystallization temperature was −3°C. The crystal-solution mixtures were introduced into the centrifuge at 6° to 7°C. In this centrifuging operation the

Table IX. Results of Secondary Crystallization and Centrifuging Tests

Test	Product	G or Milliliter	Pct or G per Liter V	P	Cr	Distribution, Pct V	P	Cr
1	Crystals	3,575	0.03	5.5	0.05	21.0	87.4	52.8
	Solution	3,720	1.08	7.6	0.43	79.0	12.6	47.2
2	Crystals	4,001	0.005	6.2	0.03	4.3	87.6	65.2
	Solution	4,275	1.05	8.2	0.15	95.7	12.4	34.8
3	Crystals	2,412	0.017	6.5	0.05	13.5	88.7	49.6
	Solution	2,660	0.99	7.5	0.46	86.5	11.3	50.4
Composite	Crystals	9,988	0.017	6.02	0.041	13.2	87.8	54.8
	Solution	10,655	1.04	7.82	0.32	86.8	12.2	45.2

crystals were not washed. The disodium phosphate crystal product of continuous plant operation would be recycled to the primary solution storage tank, and the solution would go to the hydrolysis operation. The results of the tertiary crystallization and centrifuging operations are shown in Table X.

The phosphorus content of the composite pregnant solution from the tertiary crystallization step was 0.98 g per liter. After further precipitation of phosphorus from this solution with lime and/or calcium chloride in three batch operations, red cake was recovered from each of the batches by hydrolysis. The results of the hydrolysis tests are summarized in Table XI.

The calculated overall recovery of vanadium as black cake for the entire test is 84.4 pct, if the recovery obtained in hydrolysis test 3 is applied to the entire hydrolysis operation and if it is assumed that all of the vanadium leached from the calcine is recoverable as black cake, except that in the trisodium phosphate product, the calcium phosphate product, the barren solution, and the red-cake washings.

Most of the test work on the recovery of chromium from barren solution was done on solution from this test, although the tests are described in a preceding section. The results indicated that as much as 99 pct of the chromium was recovered from the barren solution in a chrome yellow product that contained over 93 pct $PbCrO_4$. In the initial leaching, 69.3 pct of the chromium in the calcined ferrophosphorus was extracted. There were small chromium losses in the trisodium phosphate, black-cake, and calcium phosphate products. Assuming that 99 pct of the chromium could be precipitated from barren solution, as some of the batch tests indicated, the overall recovery of chromium as chrome yellow would be at least 65 pct.

Conclusions

The largest phosphate reserve in the United States occurs in the Phosphoria formation of Montana, Idaho, Wyoming, and Utah. An unusual feature of this great reserve is its content of small percentages of vanadium, chromium, and other metals. In the production of elemental phosphorus by electric furnace smelting most of the vanadium and other metals collect in the byproduct ferrophosphorus. To the authors' knowledge, the western ferrophosphorus currently produced is not being treated to recover vanadium or other values contained in it. By use of the tristage crystallization process described in this paper, vanadium black-cake, chrome yellow, and a valuable trisodium phosphate product could be recovered from western ferrophosphorus.

The tristage crystallization process starts with roasting of the vanadiferous ferrophosphorus with soda ash and salt, followed by water leaching to extract vanadium, phosphorus, and chromium. Commercial grade trisodium phosphate is produced from the primary leach solution by two crystallization and centrifuging operations. The pregnant solution from the primary crystallization step contains the recoverable metal values and more phosphorus than can be tolerated in the vanadium hydrolysis step. A third crystallization and centrifuging step, involving addition of phosphoric acid to the pregnant solution, removes about 90 pct of the remaining phosphorus as disodium phosphate and leaves only about 1 g per liter of phosphorus in the final pregnant solution. The disodium phosphate crystals are recycled to the primary solution, increasing the yield of the trisodium phosphate product. After further phosphorus purification by addition of calcium ion, the final pregnant solution is hydrolyzed to precipitate vanadium as red cake. The red cake is fused at 800°C to produce black cake, which is the usual form of vanadium for use in the production of ferrovanadium and vanadium chemicals. Chromium is precipitated as chrome yellow by addition of lead nitrate or acetate to the solution remaining after hydrolysis of the vanadium. Results of a simulated plant test indicate that about 85 pct of the vanadium, 65 pct of the chromium, and 91 pct of the phosphorus contained in western ferrophosphorus can be recovered in valuable products.

Table X. Results of Tertiary Crystallization and Centrifuging Tests

Test	Product	G or Milliliter	Analysis, Pct or G per Liter V	P	Cr	Distribution, Pct V	P	Cr
1	Crystals	1,288	0.35	4.0	0.25	11.7	95.2	11.6
	Solution	4,030	11.7	0.9	8.40	88.4	4.8	88.4
2	Crystals	1,100	0.29	2.7	0.15	9.4	90.7	6.9
	Solution	3,335	13.1	1.3	9.46	90.6	9.3	93.1
3	Crystals	2,335	0.33	3.3	0.33	11.4	94.8	14.8
	Solution	4,690	12.9	0.9	9.55	88.6	5.2	85.2
Composite	Crystals	5,243	0.33	3.4	0.27	11.1	94.3	12.1
	Solution	11,055	12.50	0.96	9.12	88.9	5.7	87.9

Table XI. Results of Hydrolysis Tests

	Test Number 1	2	3
Vanadium loss in calcium phosphate precipitate, pct	0.2	0.6	6.2
Analysis of red cake, pct: V	31.6	38.6	41.8
P	0.11	0.10	0.20
Cr	0.79	2.05	1.09
Na	5.8	8.3	8.9
Analysis of barren solution, g per liter: V	2.48	1.36	0.25
P	0.7	0.5	0.20
Vanadium precipitated by hydrolysis, pct	81.3	88.9	97.2
Analysis of black cake, pct: V	50.5	48.9	50.2
P	0.01	0.01	0.01
Cr	0.008	0.001	0.005
Mo	0.45	0.57	1.0
Na	11.5	12.2	11.0
Vanadium recovery in black cake from final pregnant solution, pct	81.1	88.3	91.0

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Directional Properties of 2S Aluminum

by K. T. Aust and F. R. Morral

The preferred orientation and earing characteristics of 2S aluminum were studied. An empirical correlation was obtained relating earing behavior and variation of mechanical properties for face-centered cubic metals. Strain-ratio measurements for 2S were found to be in good agreement with Hill's theory of plastic anisotropy.

DIRECTIONALITY in sheet metals may be revealed by earing in a cupping test, or by the variation of mechanical properties of tensile specimens taken at different angles to the rolling direction. However, no simple correlation appears to exist between earing and variation in mechanical properties in metals and alloys studied.[1-3]

Aluminum of commercial purity (known as 2S, with a specified minimum of 99.0 pct Al) cast by the direct casting process was chosen in the present investigation since ears at 45° or 0°, 90° can readily be obtained. Preferred orientation is often the principal cause of uneven metal flow, such as earing, and variation in mechanical properties. Consequently, the preferred orientation characteristics of 2S aluminum were initially studied using both X-ray diffraction and micrographic techniques. The variation of mechanical properties with angle to the rolling direction was next determined in an effort to clarify the apparent lack of correlation of earing behavior with mechanical properties for face-centered cubic metals. Strain-ratio[*][5,6] measurements were finally conducted to determine first, if the maximum values of the strain ratio occurred at the earing positions, and second, if Hill's theory of plastic anisotropy[7] is applicable to other face-centered cubic metals such as aluminum.

[*] The strain-ratio values are obtained by deriving the slope of the curve ln W/Wo vs ln T/To where Wo and To are the initial width and thickness respectively of the tensile specimen and W and T are the width and thickness at an arbitrarily chosen percentage of elongation.

Detailed treatments, working, and heat treating are not given in this paper since this study is not concerned with the methods to produce earing, but to correlate earing with other properties and characteristics of the material. The percentage of earing was measured using the formula specified by the Aluminum Association, $\frac{x-y}{x} \times 100 = \text{pct earing}$, where x is the height of the ear and y is the height of the valley from the bottom of the cup.

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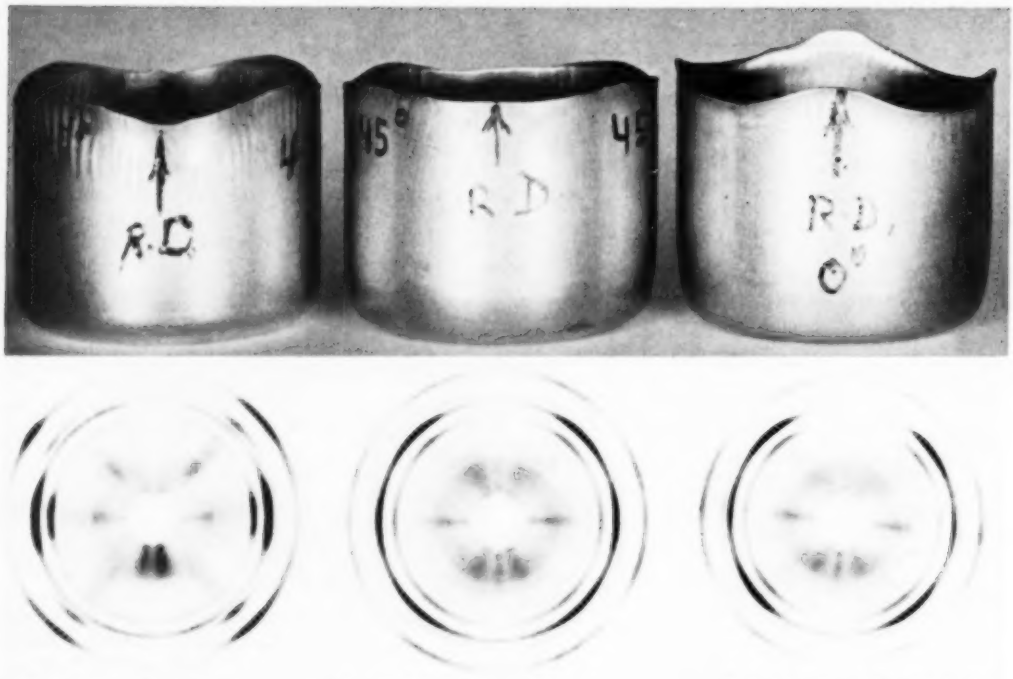
Preferred Orientation Characteristics of 2S

X-ray Studies: Beck and coworkers[8] have determined that the rolling texture of 2S after 95 pct cold reduction may be approximately described by four equivalent ideal orientations near (123) [$1\bar{2}1$]. Also, the recrystallization or annealing texture of 2S aluminum consists of four components of the (123) [$1\bar{2}1$] type, retained from the rolling texture, and of a (100) [001] or cube texture component.[9] Fig. 1 illustrates the typical appearance of deep drawn earing cups with the corresponding X-ray diffraction patterns. The X-ray patterns were taken with copper radiation using the structure-integrating method[10] in which the specimen is scanned during the X-ray exposure. The rolling direction was vertical and the rolling plane was perpendicular to the horizontal X-ray beam. It was found that an increase in the retained rolling texture component resulted in a greater 45° ear height, while an increase in the recrystallization texture component (i.e., cube texture) caused greater 0°, 90° earing.

X-ray diffraction studies of 2S cold rolled to final thickness followed by a final anneal have shown that the rolling texture, and also the retained component of the rolling texture after annealing, are increased with greater cold-rolling reduction.

The preferred orientation characteristics of 2S sheets given an intermediate anneal between cold rolling followed by a final anneal were found to depend on the position of the intermediate anneal during cold rolling. For instance, three identical samples of 2S homogenized ingot, each 1 in. thick, were given the following cold-rolling and annealing treatments: 1—50 pct reduction, intermediate anneal, 96 pct reduction to 0.020 in. and a final anneal; 2—75 pct reduction, intermediate anneal, 92 pct reduction to 0.020 in. and a final anneal; and 3—90 pct reduction, intermediate anneal, 80 pct reduction to 0.020 in. and a final anneal. The intermediate and final annealing treatments consisted of a 70°F per hr heating rate, held 6 hr at 800°F and air cooled.

Typical X-ray patterns after each of these treatments are shown in Fig. 2. It was evident that after treatment 1, the retained rolling texture component predominated; after treatment 2, the retained roll-

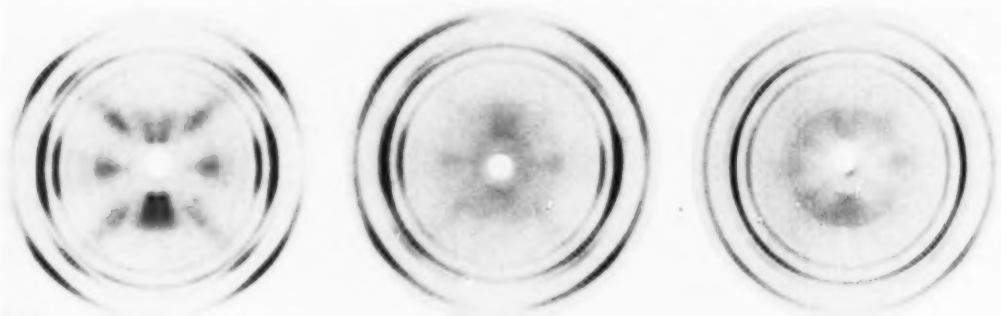


a—Typical for rolling texture. b—A mixture of 1a and 1c. c—Typical for recrystallization texture of rolled 2S.

Fig. 1—Earing cups from annealed 2S sheets with typical corresponding X-ray patterns.

ing texture component decreased and the cube texture component increased. After the treatment outlined in 3, the rolling texture component again decreased with very little cube texture, approaching a random orientation texture. These results illustrate the changes in the amounts of preferred orientation which may occur when the position of a single intermediate anneal is varied.

The importance of final annealing temperature on the preferred orientation and earing characteristics of many face-centered cubic metals and alloys has been demonstrated by various investigations.[11-14] For instance, it was determined that the 0°,90° ears of copper[14] and cupronickel[17] increased in size as the final annealing temperature was raised. The height of 45° ears in brass also increased with the temperature of the final anneal.[11, 13] The effect of final annealing temperature on the earing behavior of 2S was determined and is shown in Fig. 3. The multiple curves of Fig. 3 were obtained by various cold-rolling and intermediate annealing treatments prior to the final anneal. Therefore, the ear height and ear direction at any one final annealing temperature depended on the previous treatment. Generally, a decrease of 45° ear size and an increase of 0°,90° ear size resulted with higher final annealing temperatures. X-ray studies have revealed an increase of the cube orientation texture in 2S after annealing at higher temperatures. For both copper[14] and brass,[11, 13] it was believed that the increased grain size with resulting greater ease of plastic flow was the more important influence on increase in ear height with temperature of the final anneal. However, if the larger grain size was a contributing factor to the ear height of 2S, then both 45° and 0°,90° ear sizes would be expected to increase as the final annealing temperature was raised. Since this was not observed, the more perfectly developed



50 pct reduction, intermediate anneal, 96 pct reduction. 75 pct reduction, intermediate anneal, 92 pct reduction. 90 pct reduction, intermediate anneal, 80 pct reduction.

Fig. 2—Typical X-ray patterns of 2S sheets which were annealed as shown.

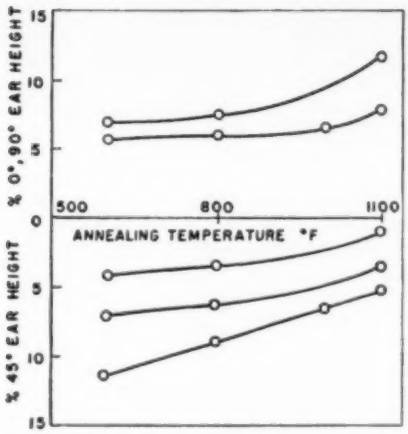


Fig. 3—Effect of final annealing temperature on the ear height of annealed 2S sheets given different cold rolling and intermediate annealing treatments.

cube orientation texture is believed to be the primary reason for the variation of ear size of 2S with change in final annealing temperature.

Micrographic Studies: The orientations present in aluminum sheet were studied micrographically, by using the new technique with an anodized film and polarized light.[9, 15, 16]

It was observed that the cube grains appeared black under polarized light and remained black even though the microscope stage was rotated through 360°. However, the other orientations changed colors from white to gray to black, and vice versa, for each 45° rotation of the stage. It was, therefore, possible to determine the percentage of cubically aligned grains. Two micrographs were taken from the same locations of a specimen before and after a 45° rotation of the microscope stage. The two negatives were superimposed such that identical grains coincided. A photographic print was then made from the two superimposed negatives. Those grains which were now black on the print possessed the cube orientation texture. The percentage of cubically aligned grains was then determined from the photographic prints using grain count techniques to an accuracy of approximately ±5 pct. These determinations were carried out near the center of the cross section of annealed 2S sheets having different 0°,90° ear heights. The percentage of 0°,90° ear height was plotted as a function of the percentage of cubically aligned grains in Fig. 4. A similar relationship was also found by Baldwin[17] for annealed copper strip. It is noteworthy for annealed 2S that sheets containing less than 40 pct cubically aligned grains still can produce ears at 0° and 90° to the direction of rolling.

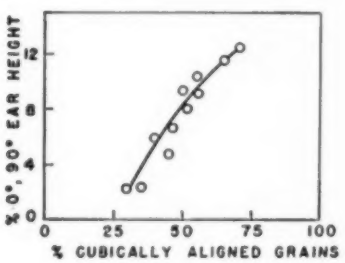
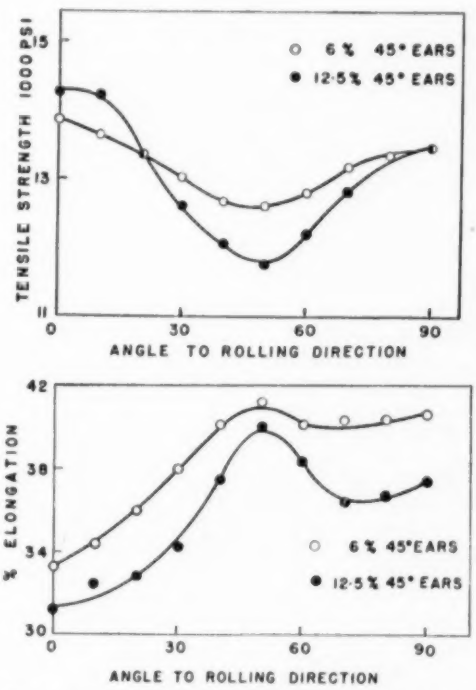


Fig. 4—Relationship between percentage of 0°,90° ear height in drawn cup and percentage of cubically aligned grains in microstructure.

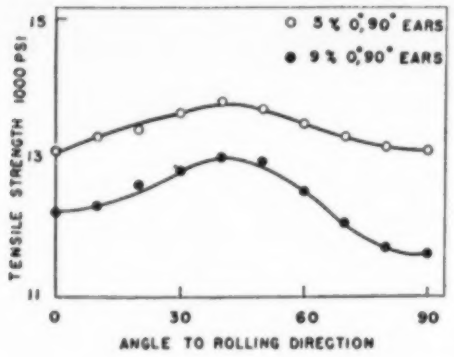
Variation of Mechanical Properties of Annealed 2S

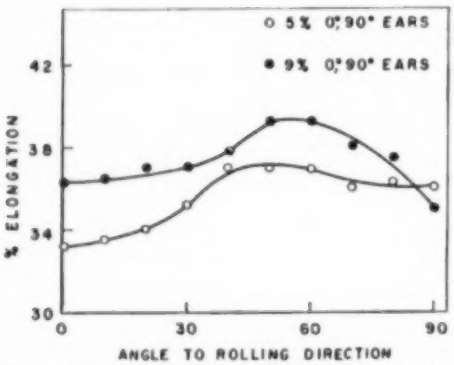
Tensile tests were conducted at every 10° from 0° to 90° to the direction of rolling, for annealed 2S sheets having different earing characteristics. The results are shown in Figs. 5 to 8. Differences in grain size produced by the treatments given influenced the actual values of the mechanical properties. However, the variation of tensile strength and percentage of elongation was a function of the angle the axis of the tensile specimen made with the rolling direction.

When 45° ears occurred in the cups, minimum tensile strength and maximum elongation was obtained in approximately the corresponding position in the sheet, i.e., at 45° to the rolling direction (Figs. 5 and 6). These results therefore agreed with those on brass,[2] also having 45° ears. When the crests of ears were located in the 0° and 90° positions the tensile values were approximately a minimum and the elongation values generally approached a minimum in the corresponding positions (Figs. 7 and 8). The results for the variation in elongation of 2S were somewhat obscured by the effect of mechanical fibering. However, the general correlation of earing and variation in tensile strength was apparent. The minimum elongation in 2S and copper[4] occurred in approximately the corresponding positions of 0° and 90° earing. The minimum elongation of copper was attributed to the high proportion of (100) [001] texture.[18] It was shown in the present work that 2S annealed sheets having 5 pct and 9 pct 0°,90° ear heights (as in Fig. 8) contained a large proportion of cube texture. Therefore, it is believed that the cube texture component of the annealing texture



Figs. 5 (upper) and 6 (lower)—Directionality of tensile properties of annealed 2S sheets with different 45° ear heights.





Figs. 7 (upper) and 8 (lower)—Directionality of tensile properties of annealed 2S sheets with different 0°,90° ear heights.

was also responsible for the minimum elongation values in annealed 2S having 0°,90° ear directions.

One obvious anomaly still remained; namely, with 0°,90° earing, 2S aluminum showed a minimum tensile strength and copper a maximum tensile strength, in the 0° and 90° directions of rolling. Richards[10] has indicated that the 0°,90° positions of ears in copper corresponded to the direction of minimum true tensile strength. Richards pointed out that an approximate estimation of the true tensile stress at fracture can be made by multiplying the tensile strength value by a factor, $1 + e$, where e is the elongation of the test piece expressed as a fraction of the gage length. By applying the $1 + e$ approximation, the true tensile strength of 2S was also determined to be a minimum at 0° and 90° to the rolling direction. Therefore, the 0°,90° earing behavior of both copper and 2S can be correlated with the minimum true tensile strength values in corresponding 0° and 90° positions. The same relationship held for annealed brass and 2S having 45° earing positions, since the directions of maximum and minimum true stress values are identical with the positions of the maximum and minimum tensile strength values.

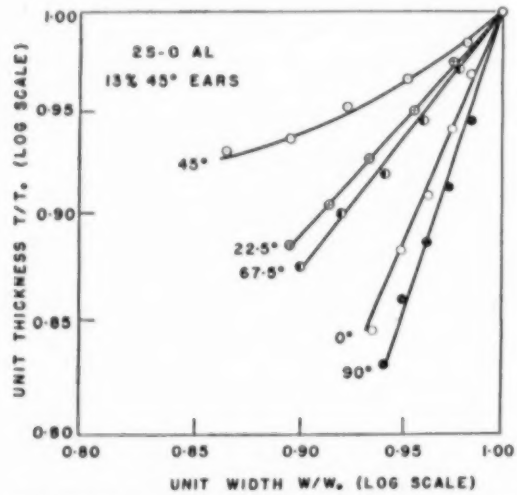
Therefore, a general empirical correlation exists between earing and variation of mechanical properties for face-centered cubic metals. The general tendency with 0°,90° or 45° earing directions is the occurrence of minimum true tensile strength in approximately the same direction of ear formation. With 45° earing, the elongation is usually a maximum at about 45° to the rolling direction. However, with 0°,90° earing, the elongation generally approached a minimum in the 0° and 90° positions.

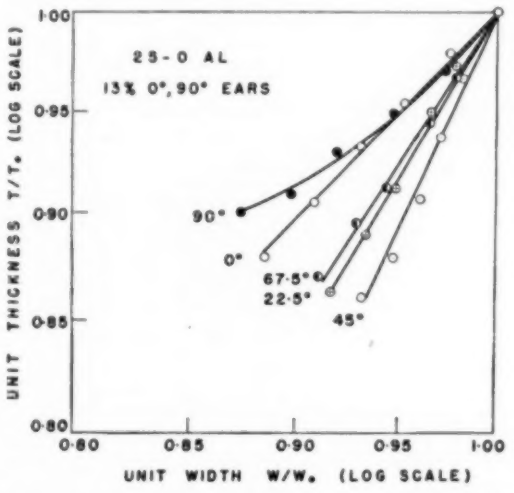
Strain Ratios of Annealed 2S

The previous correlation of directionality and earing tendencies is still only qualitative. The theory of plastic anisotropy advanced by Hill[7] appears to be a promising quantitative approach to the problem. According to this theory, the important factor controlling the positions of the ears is the relation between the ratios of the components of the stress and the plastic strain increment. The relevant test is the measurement of strain ratios in tension tests. The theoretical treatment, described by Bourne and Hill,[6] resulted in the following equation:

$$\frac{\ln W/Wo}{\ln T/To} = \frac{H + (2N - F - G - 4H)\sin^2\alpha\cos^2\alpha}{F\sin^2\alpha + G\cos^2\alpha} = r(\alpha) \quad [1]$$

Wo and To are the initial width and thickness respectively of the tensile specimen and W and T are the width and thickness at an arbitrarily chosen





Figs. 9 (left) and 10 (right)—Contraction of unit width and unit thickness during tensile tests of two samples of annealed 2S having 45° ears and 0°,90° ears.

percentage of elongation (usually every 5 pct). F, G, H, and N are parameters specifying the constant state of anisotropy. The term r is the strain ratio at an angle α to the rolling direction.

The validity of the theory expressed in Eq. 1 can be checked by comparing it with the experimental results of strain ratios at various angles to the rolling direction. According to Bourne and Hill, if N is less than both $F + 2H$ and $G + 2H$, the ears are in the 0° and 90° positions. However, if N is greater than both $F + 2H$ and $G + 2H$, the ears are in the 90° positions where γ may be obtained from

$$\tan^2\gamma = \frac{N-G-2H}{N-F-2H} \qquad [2]$$

The above theoretical considerations were found to be in good agreement with the experimental data for copper and brass having four ears.[6] The following experiments were conducted to determine if Hill's theory of plastic anisotropy may be generalized to include other metals, such as aluminum.

Two sheets of annealed 2S aluminum (0.020 in. thick) were used throughout these tests, one sheet having four ears of 13 pct height at 45° and the other having four ears of 13 pct height at 0°,90° to the rolling direction, after deep-drawing. Standard tensile specimens in duplicate were milled from these sheets at various angles to the rolling direction, 0°, 22.5°, 45°, 67.5°, and 90°. The gage length was 2 in. and the width 0.5 in. Width and thickness measurements of the tensile specimens were taken with a micrometer reading to 0.0001 in., at every 5 pct elongation from 0 pct to the stage at which necking began. The values of the width and thickness were expressed in terms of unit width (W/Wo) and unit thickness (T/To).

The unit width and unit thickness values for the two sheets of annealed 2S having 45° and 0°,90° ears were plotted logarithmically in Figs. 9 and 10. It is evident that the rate of contraction of thickness with respect to that of the width is a function of the angle between the axis of the tensile specimen and the rolling direction.

Values of strain ratios (r) were plotted as a function of the angle α between the rolling direction and the axis of the tensile specimen in Fig. 11. The maximum values of r were found to occur in the same positions as the ears; i.e., for 45° ears, r is a maximum at 45° and for 0°,90° ears, r is a maximum at 0° and 90°. It is concluded that the occurrence of maximum values of the strain ratio at the actual earing positions is not only true for copper and 70:30 brass but is also the case for 2S aluminum and perhaps for all face-centered cubic metals. Baldwin et al.[5] have explained the relationship between unit width and unit thickness, for copper samples cut at 45° to the rolling direction, by the manner in which the crystallites deform.

The theoretical relation of Hill (Eq. 1) was checked with the experimental results of r for annealed 2S over the whole range of angles to the rolling direction. The parameters giving four ears at 45° corresponding to the curve in Fig. 11 are: $F:G:H:N = 1:0.8:0.35:3.2$. According to the theory of Hill, if N is greater than both $F + 2H$ and $G + 2H$, as is true in the present case, the ears are in the 90°—γ positions. The angle γ was determined to be 47° from Eq. 2, i.e., the ears should form at 43°. This agrees well with the experimental value of 45° ears.

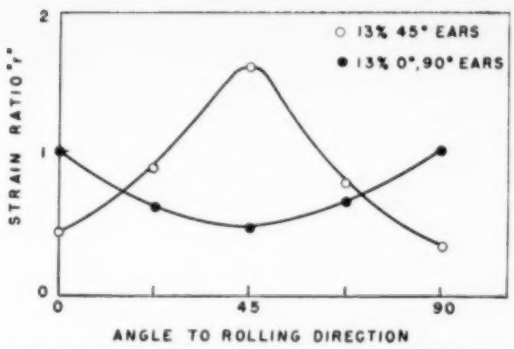


Fig. 11—Variation of strain-ratio "r" with angle to the rolling direction for annealed 2S sheets having 45° and 0°,90° ears.

The results shown in Fig. 11 for the annealed 2S sheet having 0°,90° ears were found to give the following parameters: $F:G:H:N = 1:1:1:1.6$. The theory predicts ears in the 0° and 90° positions when N is less than both $F + 2H$ and $G + 2H$, which is again in agreement with experiment.

Thus, the theory of plastic anisotropy advanced by Hill was found to be in good agreement with the experimental data for annealed 2S sheets. Since similar conclusions were reached for copper and 70:30 brass,[6] it is concluded that Hill's theory may be applicable to all face-centered cubic metals. Consequently, Hill's method of predicting earing positions from measurements of strain ratios in tension tests is regarded to be of more fundamental significance than the usual empirical attempts to correlate rupture properties with the earing tendency of a metal.

Summary

The occurrence of 0°,90° earing in annealed 2S sheet was related to the cube texture component, while 45° earing was associated with the retained rolling texture component. The preferred orientation characteristics of the final annealed 2S sheet were found to depend on the amount of reduction before the anneal, and on the position of an intermediate anneal during the cold-rolling cycle.

Micrographic methods revealed a definite relationship between the 0°,90° earing tendency of 2S aluminum and the percentage of cubically aligned grains. The amount of cube orientation texture increased with higher final annealing temperatures.

The tensile strength and true stress at fracture were a minimum and the elongation a maximum at 45° to the rolling direction when 45° ears occurred in 2S. However, the tensile strength and true stress were minima and the elongation generally approached a minimum at 0° and 90° when ears formed in the 0° and 90° positions. The variation of mechanical properties with earing behavior of annealed 2S was correlated with similar variations for other face-centered cubic metals.

The strain-ratio values were a maximum at 45° or 0° and 90° for annealed 2S sheets that eared at 45° or 0° and 90°, respectively. The theory of plastic anisotropy advanced by Hill was found to be in good agreement with the experimental results for annealed 2S sheets.

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Technical Note

Preferential Etch for Use in Optical Determination Of Germanium Crystal Orientation

by R. H. Wynne and Colman Goldberg

WHEN using an optical goniometer to determine crystal orientation[1] it is advantageous to use a preferential etchant so that the etch pits have plane faces which are parallel to crystallographic planes, all of which are of the same "form."

"Westinghouse Silver Etch" (WAg), a preferential etch for germanium, is made up as follows: 40 ml of 49.7 pct hydrofluoric acid, 20 ml of 70.7 pct nitric acid, and 40 ml of distilled water containing 2.0 g of silver nitrate. Examination of metallographs of WAg etched surfaces (Fig. 1, for example) indicates that, regardless of crystal orientation, the faces of the etch pits are (111) surfaces. Optical goniometer examination of these WAg etched surfaces also indicates that the faces of the etch pits are (111) surfaces, i.e., all bright reflections are from (111) planes.

When using an optical goniometer of the type described by Barrett,[1] not only (111) reflections from a WAg etched germanium surface but also other reflections of lower intensity will be observed. These latter reflections can cause confusion. We have used an optical goniometer made from a war surplus astrocompass and a galvanometer lamp. The reflections are observed by using the goniometer in a darkened room and letting the reflected light be incident upon a piece of white paper. The resulting decrease of goniometer sensitivity enables (111) reflections only to be observed. This in turn permits the crystal orientation to be determined in a matter of minutes, since only two measurements are necessary.

Fig. 1—WAg etched germanium surface. Approximately (111) orientation.

The authors wish to acknowledge the help received from R. E. Davis who assisted in making the metallographs and aided the authors in the interpretation of the metallographs.

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TN 146E. Manuscript, Oct. 16, 1952.

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Some Applications of the Thermodynamic Theory of Irreversible Processes to Physical Metallurgy

by E. S. Machlin

An extension of the thermodynamic theory has been made for the case of irreversible growth processes occurring by the motion of an interface. The theory is applicable to such diverse phenomena as diffusion, growth in recrystallization, continuous grain growth, growth of carbides, etc., growth of eutectoid products, growth in solidification, recovery, "slipless" flow, etc.

THE publication of a recent book[1] has served to focus attention on a very powerful means of treating certain irreversible processes. This method which has been formally described as the thermodynamic theory of irreversible processes is applicable to processes which involve an approach to equilibrium and for which the deviations from equilibrium are small. The irreversible processes can be classified into three groups: chemical reactions, transport processes (diffusion, heat and electrical flows), and relaxation phenomena involving a degradation of internal energy to more stable states. The limits of applicability of the theory can be precisely defined[1, 2] for each type of irreversible process. For example, in a chemical reaction at constant temperature and pressure, the Gibbs free energy released per mol in the process should be less than the thermal energy, RT.

Another type of irreversible process, which sometimes involves a combination of the first two of the above-mentioned groups, is treated in this paper. This process is one characterized by the motion of an interface separating two regions having different values of free energy and may be briefly described as a growth process. Prigogine[2] and Herring[3] have treated special cases of this type of process.

Previous conscious applications of the theory in metallurgy have been limited to the field of diffusion, one of the transport processes. Darken,[4] Bardeen,[5] Prigogine[2] and others have made significant contributions in this respect. Some other applications of the theory are described in this paper.

The Theory

The thermodynamic theory of irreversible processes is based on the work of Onsager,[6] DeDonder,[7] Prigogine[2] and others. A resume of the theory has been given by Prigogine[2] and DeGroot.[1] A brief description of the theory follows, although for a complete understanding the reader is urged to read the references.

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It is first assumed that the change in entropy, even for a system removed from equilibrium, is given by

$$dS = [dU + pdV - \Sigma_i \mu_i\, dn_i - \Sigma_k P_k\, dx_k]T^{-1}$$

Using this expression, the irreversible entropy production in the system is calculated by subtracting the contribution to the change in entropy of the system by transfer of heat, work, or matter from the surroundings. Thus, for example, the irreversible entropy production of a system at constant temperature and pressure is given by

$$d_i S = -\frac{1}{T}\, dG \qquad \text{(DeDonder[7])}$$

Now it has been shown by Prigogine,[2] DeDonder,[7] and DeGroot[1] that the rate of irreversible entropy production $d_i S/dt$, when calculated in the manner suggested, can be written as a sum of products of conjugate forces X_k and fluxes J_k, i.e.,

$$\frac{d_i S}{dt} = \Sigma_k J_k X_k \qquad \text{[I-1]}$$

The assumption is next made that a linear relation exists between a given flux and the forces, obtained from Eq. I-1, i.e.,

$$J_i = \Sigma_k L_{ik} X_k \quad (i = 1, 2, \ldots n) \qquad \text{[I-2]}$$

Generally, there is a degree of freedom in choice of the fluxes and forces. However, for all the choices consistent with Eq. I-1 the Onsager[6] relations, based on the principle of microscopic reversibility, namely, $L_{ik} = L_{ki}$, are valid. The coefficients L_{ik}, depending upon the choice of the conjugate fluxes and forces, may be more or less dependent upon the parameters defining the state of the system. In general, the proper choice of fluxes and forces utilizing Eq. I-1, makes the coefficients L_{ik} independent of time. Also, because many of the three classes of irreversible phenomena have already been treated,[1, 2] a proper choice can be made by analogy. In any case, the validity of Eq. I-2, from whatever choice made using Eq. I-1, must be tested by experimentation.

The theory, thus, comprises the following steps: 1—The irreversible entropy production is calculated to yield Eq. I-1. 2—The terms in Eq. I-1 are grouped

to yield what seems to be a logical compilation of conjugate fluxes and forces. 3—The linear relations, Eq. I-2, are set up using these definitions of fluxes and forces. 4—These linear relations are then tested experimentally. 5—The reciprocal relations $L_{ik} = L_{ki}$ are also checked experimentally.

Upon experimental verification of the predicted results for a large number of diverse types of irreversible processes, it has been found that the theory provides a neat, concise description of irreversible phenomena in the state not too far removed from equilibrium.* Thus, the theory fulfills one of the goals of scientific endeavor. It is beyond the scope of this paper to illustrate the breadth of applicability of the theory. However, an attempt will be made in this paper to illustrate how the theory rationalizes growth phenomena on the basis of the simple principles just described.

* The limit of applicability of the theory can be made precise for each type of irreversible process.

Before concluding this section it is worthwhile to note that the thermodynamic theory in each case comprises the first approximation of the corresponding kinetic description. The thermodynamic theory of irreversible processes is valid, therefore, only when the second term in the expansion of the kinetic description is an order of magnitude smaller than the first term. This situation, for the example of an irreversible process at constant temperature and pressure, exists only when the free energy per atom released in the irreversible process is less than the thermal energy kT. A major advantage of the thermodynamic theory as compared to the statistical mechanical treatment is that the former is independent of any assumption about model. Within its realm of applicability, the theory gives an accurate phenomenological description of nature, quite analogous to the description ordinary thermodynamics gives of the state of equilibrium. An appreciation of this fact can only be gained by reading DeGroot[1] and Prigogine.[2]

Extension of the Theory

Previous considerations of growth phenomena in the light of the theory have been few. All of these treatments[3-5] have considered some specific growth process as the resultant of the one or two basic types of irreversible phenomena (transport and chemical reactions) rather than as an entity itself. It occurred to this author that a consideration of the growth process as a separate type of irreversible phenomenon would be extremely simple as compared to previous treatments and would involve no assumption about mechanism.

Growth phenomena at constant temperature and pressure are characterized by the motion of an interface separating two regions having different values of free energy. The basic equation for the rate of production of irreversible entropy per unit area of interface is given by

$$\frac{d_i s}{dt} = -\frac{1}{TA}\frac{dG}{dt} \qquad [I\text{-}3]$$

where G is Gibbs free energy for system; A, the interfacial area; and T, the absolute temperature. In order to use Eq. I-3 in the sense desired (assuming that Eq. I-2 can be applied to the result), the rate of decrease of the free energy must be expressed in terms of the interface. For example, consider the case of a sphere of phase i growing out into the less stable phase o, and assume that the interfacial energy σ is isotropic. In this case,

$$\frac{dG}{dt} = \frac{\partial G}{\partial R}\frac{dR}{dt} = \{(-g_o + g_i)\,4\pi R^2 + 8\pi R\sigma\}\frac{dR}{dt} \qquad [I\text{-}4]$$

where R is the radius of sphere, and $g_{o,i}$ the free energy per unit volume of phases o, i, respectively. It should be noted that Eq. I-4 corresponds to the situation where no other parameter that is descriptive of the interface varies with time. For example, in one conceivable growth process—the growth of spheres of cementite from supersaturated ferrite—two additional parameters might vary with time, namely, the thickness of the diffusion layer normal to the interface and the free energy g_o' of that part of the diffusion layer adjoining the interface. In this case two additional terms need to be added to the expansion of dG/dt. Unless otherwise specified the growth phenomena treated in this paper correspond to the situation described by Eq. I-4.

Substituting for dG/dt and A in Eq. I-3, using Eq. I-4, the following equation is obtained:

$$\frac{d_i s_i}{dt} = \frac{1}{T}(\Delta g - 2\sigma/R)\frac{dR}{dt} \qquad [I\text{-}5]$$

where $\Delta g = g_o - g_i$.

As expected, Eq. I-5 has the form of a product of a force, $\dfrac{\Delta g - 2\sigma/R}{T}$, and a conjugate flux, dR/dt. The force is the free energy released per unit advance of a unit area of interface. The flux is the rate of advance of the interface normal to itself. The next step in the theory is to assume that the flux is linearly related to the force, or

$$\frac{dR}{dt} = L_R\frac{\Delta g - 2\sigma/R}{T} \qquad [I\text{-}6]$$

In words, this assumption of the phenomenological theory is that the rate of advance of an interface is proportional to the free energy released per unit advance per unit area of interface. Eq. I-6 should be applicable to all situations meeting the conditions assumed in the derivation and also the limitation that $(\Delta g - 2\sigma/R) \times$ atomic volume $<< kT$.

If now it can be shown that the Eqs. I-3 to I-6, or equivalent equations derived from Eq. I-3, are consistent with experiment, then one use of the thermodynamic theory of irreversible processes will have been demonstrated. Although it is true that Eq. I-6 could have been assumed *a priori*, so could any of a number of other relations have been assumed. The function of the thermodynamic theory in this respect is to provide a criterion which relations of the type Eq. I-6 must satisfy in order to be consistent with the theory. The value of this, or any other, phenomenological theory is the existence of a formalization that describes what appear to be diverse phenomena in terms of some language common to all the phenomena.

Theory Applied to Grain Boundary Migration

Growth of a Recrystallized Grain in a Strained Matrix: Consider the case of a single, spherical, strain-free, monocrystalline grain growing in a polycrystalline strained matrix. Let g_o be the free energy per unit volume of the strained matrix, and

g_v the free energy per unit volume of the unstrained matrix. Eq. I-6 applies directly to this case, hence the rate of nucleus growth is given by Eq. I-6, i.e.,

$$\frac{dR}{dt} = \frac{L_v}{T}(\Delta g - 2\sigma/R) = G - B/R \qquad [II\text{-}1]$$

This equation states in effect, that after a time t_o (nearly equal to the induction period), B/R becomes very much smaller than G, and hence that after this time, t_o, the growth rate is apparently constant. Reasonable estimates of Δg and σ lead to the minimum R for this range as about 10^{-5} cm. This result checks the experimental observations of Mehl and coworkers[8, 9] upon the growth of strain-free crystals in a strained matrix; that is, from observations of strain-free crystals larger than 10^{-2} cm, the growth rate is a constant.

An approximate relation between the induction period and the growth rate can be derived by integrating Eq. I-6 and making suitable approximations. The result is that the induction period is approximately inversely proportional to G, i.e.,

$$t_o \cong \frac{10\,\sigma}{\Delta g\, G}$$

Thus, a plot of log t_o vs log G should yield a straight line having the slope, -1 and the intercept $10\,\sigma/\Delta g$ at unit growth rate. Data taken from Anderson and Mehl[8] have been plotted in this manner in Fig. 1. As shown by the figure, the data for various temperatures and percentage of prior elongation do approximately obey the predicted relations.**

** This result implies that the induction period does not correspond to a time for nucleation, contrary to the assumptions of Anderson and Mehl[8] and Turnbull.[10]

Further, a comparison of the experimental and theoretical intercepts yields a value of 400 for the ratio $\Delta g/\sigma$. Assuming a value of $\sigma = 500$ ergs per sq cm, a value of $\Delta g = 2\times10^5$ ergs per cu cm is obtained. This value compares favorably with the value estimated, on the basis of the stored strain energy using 5 pct as the ratio of the energy stored to the work of deformation, namely,

$$\Delta g \text{ (estimated)} = 0.05 \times \text{(work done)} = 0.05 \times 3.5 \times 10^7 = 2 \times 10^6 \text{ ergs per cu cm}$$

If this estimate is meaningful, then about 90 pct of the energy stored during cold work is relaxed by recovery prior to recrystallization. Both these energies when related to one atom are much less than kT. Thus, the application of Eq. I-6 to nucleus growth in recrystallization is justified.

Another interesting result is obtained by considering the contribution of the grain boundaries in the strained phase to Δg. For the data of Anderson and Mehl, this energy corresponds to about 500 $\sigma_{s\text{-}s}$ (corresponding to a grain size of 530 grains per sq mm). Inasmuch as $\sigma_{s\text{-}s}$ is expected to be of the order of magnitude of σ, but less than σ, this result, when compared to the previously calculated value of $\Delta g = 400\,\sigma$, implies that the surface energy contribution to Δg is as important as the strain energy contribution. The fact that both the initial grain size and the amount of deformation affect the growth rate is confirmation of this conclusion.

It is instructive to separate the strain energy term, Δg_ϵ, from the surface energy term, Δg_b, in Δg proper. Whenever, the growing strain-free and internal, boundary-free, material is surrounded by a matrix comprising both strain and grain boundaries, then Eq. I-6 becomes

$$\frac{dR}{dt} = \frac{L_v}{T}(\Delta g_\epsilon + \Delta g_b - 2\sigma/R) \qquad [II\text{-}3]$$

where

$$\Delta g = \Delta g_\epsilon + \Delta g_b$$

When R is much larger than the average diameter of the grains surrounding the growing grain, then

$$\Delta g_b = A \cdot \sigma_{s\text{-}s}$$

where A is the grain boundary area per unit volume, sq cm/cu cm, and $\sigma_{s\text{-}s}$ is the interface energy between strained grains per unit area.

Secondary Recrystallization: The growth of exaggerated grains in secondary recrystallization can be understood on the basis of Eq. II-3. For the case of secondary recrystallization, $\Delta g_\epsilon = 0$. Hence, the equation becomes simply

$$\frac{dR}{dt} = \frac{L_v}{T}\left(\Delta g_b - \frac{2\sigma}{R}\right)$$

This dependence of growth rate upon the radius has been obtained experimentally by Rosi et al.[11] in the secondary recrystallization of silver. In their case, measurements of growth rates have been made during the induction period which confirm Eq. II-4 qualitatively. More information is required before a quantitative check can be made. They found that R^* defined by

$$R^* = \frac{2\sigma}{\Delta g_b}$$

was about twice the average matrix grain radius. R is the smallest grain radius of the secondary type which can grow spontaneously outward. Thus, as expected, the necessary and sufficient condition for secondary recrystallization is that the secondary grain radius R obey the criterion

$$R > R^* = \frac{2\sigma}{\Delta g_b} = CD_{avg.} \qquad [II\text{-}5]$$

where $D_{avg.}$ is the average matrix grain size (diameter) and C is a constant (equals 1 for two dimensional recrystallization); while the secondary grain is surrounded by primary grains. If the average grain diameter is restricted in its growth, then secondary growth can occur at a fast rate. If on the other hand the matrix grains can grow, the rate of growth of secondary grains will either be small or nonexistent.

No limit is placed by the theory on the origin of the secondary grains. They can be formed by growth of existing grains which obey the growth criterion Eq. II-5, or a similar criterion derived from Eq. II-3 whenever Δg_ϵ is not zero across some grain boundaries (some internal strains exist), or by a true recrystallization. It is believed however, that the first two alternatives are the most reasonable.

Continuous Grain Boundary Migration: The last case that can be treated under the general classification is that defined by $\Delta g_\epsilon = \Delta g_b = 0$. This is the case of grain boundary migration under a surface energy gradient. For this special case

$$\frac{dR}{dt} = \frac{L_v}{T}(-2\sigma/R) \qquad [II\text{-}6]$$

Thus, grain boundary migration of this type is characterized by a decreasing dR/dt, rather than an increasing dR/dt. In other words, migration is always in the direction of the center of curvature. An extension of this concept to the continuous grain growth that occurs after recrystallization implies, as expected, that grain growth occurs by the disappearance of grain boundaries.

An interesting effect is predicted if impurities travel with the grain boundary, such that, as the total boundary area decreases, the concentration of impurities at the grain boundary increases. In this event, the differentiation of the free energy in Eq. I-4 introduces another term into the bracketed term of Eq. II-6, namely,

$$-\Sigma_i \frac{\partial \sigma}{\partial C_i} \frac{\partial C_i}{\partial R}$$

But

$$C_i = N_i/4\pi R^2$$

where N_i is the total number of impurity atoms of type i traveling with the grain boundary. Thus,

$$\frac{\partial C_i}{\partial R} = -N_i/2\pi R^3$$

Let

$$K_i = \frac{\partial \sigma}{\partial C_i} \frac{N_i}{2\pi}$$

then Eq. II-6 becomes

$$\frac{dR}{dt} = \frac{L_r}{T}\left(\Sigma K_i/R^3 - 2\sigma/R\right) \qquad [II\text{-}7]$$

For positive values of $\partial\sigma/\partial C_i$, because the net effect of grain boundary migration in ordinary grain growth is to produce grain boundaries having larger R, there will be a limitation to the size of the grains produced, given by

$$\Sigma_i K_i/R^3 = 2\sigma/R$$

For negative values of $\partial\sigma/\partial C$, when $\Sigma_i K_i/R^3$ is large compared with $2\sigma/R$, the approximate law of grain growth predicted by Eq. II-7 is[***]

[***] This method follows the assumption made by others that $D \sim R$, or that $dD/dt = -2\ dR/dt$.

$$D = \left(\frac{4L\Sigma K_i}{T}\right)^{1/3} t^{1/3}$$

When $\Sigma K_i/R^3 << 2\sigma/R$, the corresponding result is

$$D = \left(\frac{L4\sigma}{T}\right)^{1/2} t^{1/2}$$

Experimentally, it is found that the exponent of the time, t, varies between ¼ and ½ as just predicted. Thus, the explanation for the time dependence of grain growth may involve an effect of grain boundary composition upon the surface energy. It is significant in this respect that the exponent is found to approach ½ with increasing temperature of grain growth and with increasing purity of the matrix. This former trend is what would be expected, because as the temperature is increased the concentration of impurities at the boundary is decreased. The exponent ½ corresponds to no impurities in the grain boundary.

Finally, the result obtained by Zener, namely that the limiting grain diameter depends upon the particle impurities according to

$$D = \frac{2r}{f}$$

where r, the average radius of particles, and f, the volume fraction of particles, is also obtained from Eq. I-4, when the grain boundary area intersected by the particles is taken into account.

Effect of Diffusion across Boundary on Grain Boundary Migration Rate: In view of the fact that both grain boundary migration[5] and diffusion[8] occur as a result of vectorial forces, interaction effects are to be expected whenever these phenomena occur simultaneously. The phenomenological equations should then take the form

$$\frac{dR}{dt} = \frac{-L_{11}}{T}\frac{2\sigma}{R} - \Sigma_i L_{2i}\frac{\partial \mu_i}{\partial R}$$

$$\frac{dm_i}{dt} = \frac{-L_{i1}}{T}\frac{2\sigma}{R} - \Sigma_k L_{ik}\frac{\partial \mu_k}{\partial R}$$

$$L_{ik} = L_{ki}$$

where dm_i/dt is the number of atoms of kind i flowing across unit area of the boundary per second. These equations apply to the cases of cylindrical or spherical symmetry in μ_i and the grain boundary and isotropy in σ. Equivalent equations can be derived for nonsymmetrical configurations.

The qualitative implications of these equations are rather obvious. The grain boundary migration behavior should be materially affected by diffusion across the boundary, especially for the case of unequal diffusion rates (a net current of vacancies). No quantitative data are as yet available to check the equations. One of the predictions that can be made on the basis of Eq. II-8 is that for sufficient net diffusion into a spherical grain, the grain may be made to grow rather than disappear.

Effect of Temperature Gradient, etc. on Grain Boundary Migration: Another interesting interaction should occur between grain boundary migration and either a flow of electrical charge or heat across the boundary. These effects should be second order compared to the effect of diffusion across the boundary. The stationary states of zero flow of charge or heat imply that a nonzero electric potential and temperature differential, respectively, will exist across the moving interface and will be proportional to the curvature and to the interface energy σ. In particular, for the flow of heat, the phenomenological equations are

$$\frac{dR}{dt} = \frac{-L_{11}}{T}\frac{2\sigma}{R} - \frac{L_{1u}}{T^2}\,\text{grad}\,T$$

$$\frac{dQ}{dt} = \frac{-L_{u1}}{T}\frac{2\sigma}{R} - \frac{L_{uu}}{T^2}\,\text{grad}\,T \qquad [II\text{-}9]$$

The stationary state $dQ/dt = 0$, yields the equation

$$\Delta T = -\frac{L_{u1}}{L_{uu}}T\frac{2\sigma}{R}$$

Here ΔT represents the temperature increase due to the transfer of energy across the grain boundary analogous to the Dufour effect[1] in diffusion. The magnitude of ΔT is expected to be less than 10^{-3} °C.

Theory Applied to Rate of Growth of Stable Phase

Consider a spherical region of the stable phase growing in a supercooled or superheated matrix. If the theory is applicable to this phenomenon, then the

rate law should be given by Eq. I-6, where g_o is the free energy per unit volume of the supercooled or superheated matrix and g_i is the free energy per unit volume of the stable phase. Here again σ is the interfacial energy per unit area.

For the case of uniform growth of a crystal comprising a single component from the vapor phase, the bracketed term of Eq. I-6, $\Delta g - 2\sigma/R$, is proportional to the difference between the actual and equilibrium values of the vapor pressures. The experimental observations are in agreement with this rate equation for the case of uniform growth.[12] In experiments, such as those just described, whenever the change in free energy per unit volume in the presence of plane interfaces can be determined with a given accuracy, then it should be possible to determine σ with the same percentage accuracy. It is necessary, however, in order that the term $2\sigma/R$ be significant that Δg be small, i.e.,

$$\Delta g = \Delta h\, \Delta T/T_e$$

where Δh is the enthalpy of phase change per unit volume and T_e is the temperature of equilibrium for phase change. In this case errors in σ are likely to be large.

Whenever two irreversible processes such as diffusion and chemical reactions are involved in the motion of an interface, Eq. I-6 must be re-examined to see whether it applies to the physical situation being considered. For certain special cases, where the diffusive flux is linearly related to the rate of motion of the interface (as a result of the conservation of mass), Eq. I-6 can still be applied. However, there are many examples of growth processes where this simple picture is inadequate and a more detailed treatment is required. In all these cases it should be remembered that a chemical reaction involves a scalar flux while diffusion involves a vector flux. There can be no interactions between them in the sense of the theory; that is, in the event of a homogeneous distribution in the unstable phase having the correct stoichiometric relationship between components, the heterogeneous chemical reaction, proceeding by an interface motion, will not induce diffusion. An example of such a situation is the growth of an ordered phase within a disordered lattice, which incidentally should conform to Eq. I-6. These complex processes are outside the scope of the present treatment, but within the scope of the thermodynamic theory.

Theory Applied to Growth of Stable Phase in Supersaturated Matrix

As indicated in the last section, whenever a growth process involves both a chemical reaction as well as diffusion, it is worthwhile deriving the rate equations from first principles, Eq. I-3. In general, the growth of a stable phase from a supersaturated matrix involves both these irreversible processes.

Growth of Noncoherent Precipitates: Consider the growth of a spherical precipitate. There are two fluxes to consider. Namely, a diffusive flux and a chemical reaction. The rate of growth is directly proportional to the rate at which the chemical reaction $o' \rightarrow i$ proceeds, and is given by

$$\frac{dR}{dt} = \frac{L_c}{T}\,(\Delta g - 2\sigma/R)$$

where $\Delta g = g_o' - g_i$, the difference in free energy per unit volume (for a plane interface) between the regions just before and just after the interface. The free energy g_o' may vary with time.

The assumption will be made that there are at most only two constituents which can diffuse (in addition to vacancies). For each constituent the diffusive flux will be given by

$$J_i = -L_{ii}\frac{\partial \mu_i}{\partial x} - L_{ik}\frac{\partial \mu_k}{\partial x}$$

where $\partial \mu_i/\partial x$ is the gradient of chemical potential of species i normal to the interface. As pointed out by Bardeen and Herring[5] the term $L_{ik}\dfrac{\partial \mu_k}{\partial x}$ involves a factor which is generally an order of magnitude smaller than the diagonal factor. Hence, it will be neglected in the following. Now, for the case of diffusion adjacent to the interface, because diffusion is normal to the interface, by the conservation of mass

$$-J_i = \frac{d}{dt}\,\frac{(C_o)_i - (C_o')_i}{2}\,h = \frac{(C_o)_i - (C_o')_i}{2}\,\frac{dh}{dt} - \frac{h}{2}\,\frac{d\,(C_o')_i}{dt}$$

where $(C_o)_i$ is the concentration of i in phase o; $(C_o')_i$ is the concentration of i in phase o' at interface, and h is the distance normal to interface where gradient of concentration of i exists. In this equation the second factor will be assumed small compared to the first factor. Thus, to a first approximation, the relation

$$\frac{(C_o)_i - (C_o')_i}{2}\,\frac{dh}{dt} = L_{ii}\,\frac{\Delta \mu_i}{h}$$

is obtained by equating the two expressions for J_i. Now,

$$\Delta \mu_i = (\mu_o)_i - (\mu_o')_i$$

Although both $(\mu_o')_i$ and $(C_o')_i$ should vary slightly with time, it will be assumed that the variation is sufficiently small as to leave the ratio $\Delta \mu_i/\Delta C_i$ invariant with time compared to the variation of h with time. Hence, separating variables and solving for h,

$$\frac{h^2}{t} = 4L_{ii}\,\frac{\Delta \mu_i}{\Delta C_i}$$

This is the relation obtained from diffusion theory, i.e., the variable x^2/t = constant.

One more relation exists as a result of the conservation of mass, namely,

$$-J_i = \{(C_i)_i - (C_o')_i\}\,\frac{dR}{dt}$$

where $(C_i)_i$ is the concentration of i in phase i. Equating this expression for J_i to $L_{ii}\,\Delta \mu_i/h$, and substituting for h, then

$$\frac{dR}{dt} = K/t^{1/2} \qquad \text{[II-10]}$$

where

$$K = (L_{ii}\,\Delta \mu_i\,\Delta C_i)^{1/2}/2\{(C_i)_i - (C_o')_i\}$$

In this equation K is slightly dependent on time.

Eq. II-10 has been obtained independently by Zener[13] and is consistent with the data on growth of spherical carbides in supersaturated ferrite. It is interesting to note that if $(C_o')_i$ is assumed to be the composition of i in equilibrium with the stable

phase, then $\Delta g - 2\sigma/R$ equals zero, and the interface would not move. Hence, $(C_\alpha')_1$ cannot be the equilibrium composition, contrary to some previous treatments of this problem.

Growth of Pearlite: In order to obtain an expression for the growth rate of pearlite it is necessary to consider three irreversible processes: diffusion, the chemical reaction austenite† to ferrite and the chemical reaction austenite† to cementite. From such a consideration it can be shown that the linear growth rate of pearlite per unit area of interface is given by††

† The austenites in these cases differ from the nominal eutectoid composition.

†† The driving force $\Delta g - 2\sigma'/S_p$ times the atomic volume is less than the thermal energy kT.

$$V = \frac{L_p}{T(a + S_p)}\left(\Delta g - \frac{2\sigma'}{S_p}\right) \qquad [II\text{-}11]$$

where Δg is the free energy released on converting 1 cu cm of austenite to ferrite plus cementite neglecting interfacial energies; σ', the interface energy per unit area between ferrite and cementite; S_p, the interlamellar spacing of pearlite; and a, a factor comprising the three mobilities for the three irreversible processes.

An interesting result of the theory is the denial of the validity of Zener's derivation for the maximum growth rate. According to Zener[14] the maximum rate of growth occurs when half the available free energy is used to produce ferrite-cementite interfaces, the remainder being dissipated in the irreversible process of diffusion. It is apparent that if no free energy is dissipated in the chemical reaction, austenite (at interface) to pearlite, then the rate of the chemical reaction would be zero. Hence, not all of the free energy is irreversibly dissipated by diffusional processes. Further, the value of the interlamellar spacing corresponding to the maximum rate of growth is given by

$$(S_p)\ \max = \frac{4\sigma'}{\Delta g} + a/2 \qquad [II\text{-}12]$$

to a good approximation. Zener's result corresponds to $a = o$. Because the parameter a comprises a positive combination of nonzero constants it cannot equal zero. It is on the order of magnitude of S_p. In fact, if the assumption is made that as much free energy is dissipated irreversibly in the chemical reaction austenite (at interface) to pearlite as in the associated diffusion process, then

$$a = S_p$$

There is no reason however for making this assumption, because a is a well-defined parameter that is independent of such assumptions. Specifically,

$$a = \frac{L_d}{L_1} + \frac{L_d}{L_2}$$

where L_d is the mobility for the diffusion process; L_1, the mobility for the reaction austenite (at interface) to ferrite; and L_2, the mobility for the reaction austenite (at interface) to cementite.

Thus, the parameter a to a good approximation is exponentially dependent on temperature through an activation energy term, i.e., $\exp(-Q/RT)$, where Q, the activation energy, is equal to the activation energy for diffusion of carbon in austenite less the activation energy for the reaction austenite at interface to ferrite. (The assumption is made here that the activation energy for either chemical reaction is about the same.) Thus, the temperature dependence of the interlamellar spacing may be either that suggested by Zener[14] if the second term of Eq. II-12 is small compared to the first or that found by Mehl[15] if the first term is small compared to the second term.

Because the interlamellar spacing is a function of the free energy dissipated in the transformation, the velocity of motion of the interface in this case is not simply proportional to the free energy dissipated per unit advance of the interface, see Eq. II-11. Thus, the simple statement that the motion of an interface is proportional to the free energy released per unit advance of the interface is not always equivalent to results derived from the thermodynamic theory of irreversible processes; see also the results of the last section.

Theory Applied to Plastic Deformation

Growth of a Dislocation Ring: Consider that at its inception a dislocation ring defines a circular region in a plane across which shear stress has been relaxed. The ring itself comprises the interface region. There is a linear tension τ associated with the ring equivalent to the surface tension associated with a grain boundary. The tension of a ring comprising a single dislocation singular line, for example, is approximately given by

$$\frac{Gd}{2\pi} \ln R/2d \text{ ergs per cm}$$

where G is the modulus of rigidity; d, the atomic spacing; and R, the radius of ring.

Instead of using Eq. I-6 for this problem, the fundamental Eq. I-4 may be employed. The rate of decrease of free energy is simply the rate of performing work on the specimen less the rate of storing energy in the ring. Analytically, this relationship is

$$\frac{dG}{dt} = -F\frac{dl}{dt} + \tau\frac{dR}{dt} = -\sigma A_o\frac{dl}{dt} + \tau\frac{dR}{dt}$$

where F is the applied tensile load; σ, the applied tensile stress; and A_o, the cross-sectional area of specimen. In this case, it is assumed that only one dislocation ring is growing and that there are no other contributions of plastic origin to the lengthening of a specimen pulled in uniaxial tension. Further it is assumed that

$$\frac{dl}{dt} \sim \frac{d(\pi R^2)}{dt}$$

(i.e., an increase in length is due to a proportional increase in the area across which slip has occurred). Also, it is desired to calculate the entropy production per unit length of ring. Using the DeDonder relation,

$$\frac{d_i s_i}{dt} = \frac{1}{T}(C_1\sigma\text{-}\tau/2\pi R)\frac{dR}{dt}$$

Using Eq. I-2 and assuming the thermodynamic theory to apply to this case, then

$$\frac{dR}{dt} = \frac{L}{T}(C_1\sigma\text{-}\tau/2\pi R) \qquad [II\text{-}14]$$

This equation is limited to the situation where σ

times the volume per atom is less than kT. For σ = 10,000 psi, then the temperature range where Eq. II-14 is applicable is above about 1000°C. This equation should be equally applicable to the rate of growth of a slip band. Unfortunately only indirect methods are available to check this result and these methods do not yield definitive answers.

"Slipless" Flow: The irreversible process of slipless flow investigated recently by Udin and associates[16] can be treated by this theory. Herring[17] has already given one treatment based on the flow of vacancies under a chemical potential gradient, an alternate and equivalent treatment makes use of Eqs. I-2 and I-1. Using the DeDonder relation the rate of production of irreversible entropy per unit volume of specimen is

$$\frac{d_i s}{dt} = \left\{ \frac{W - \pi R\,(\gamma_s - \gamma_b RN/L)}{\pi R^2 L} \right\} \frac{dl}{dt} = \sigma \frac{d\epsilon}{dt}$$

where W is the external force on specimen; γ_s, the surface free energy per unit area; γ_b, the interface free energy per unit area; R, the radius of specimen; L, the gage length of specimen; N, the number of grain boundaries in length L; σ, $\frac{W - \pi R\,(\gamma_s - \gamma_b N\,R/L)}{\pi R^2}$ = "apparent" stress; and $d\epsilon = dL/L$ = natural strain. The limitation that σ times the volume per atom be much less than kT is obeyed for the experiments of Udin. Hence, by the assumption of the thermodynamic theory

$$\frac{d\epsilon}{dt} = L_v \sigma \qquad \text{[II-15]}$$

where L_v is the mobility related to the migration of vacancies. These results are the same as those already derived by Herring[18] and checked by Udin.

Recovery: For the phenomenon of recovery occurring uniformly over a macroscopic volume, the thermodynamic theory states that the rate of approach to equilibrium is proportional to the deviation from equilibrium. The appropriate state variable for recovery is the average‡ internal strain,

‡ Root-mean-square average is more appropriate than the arithmetic average which equals zero.

hence

$$\frac{d\epsilon}{dt} = -L\epsilon \qquad \text{[II-16]}$$

This equation is checked by experience with recovery phenomena[18] where the limitation that the average internal stress times the volume per atom is less than the thermal energy, kT, is obeyed.

Discussion of Results

The fact that many of the irreversible processes that interest metallurgists are within the scope of the thermodynamic theory of irreversible processes is fortunate, because the theory is very useful in providing a brief and general method of classifying diverse rate phenomena. If nothing else is obtained from the application of the theory, the pedagogic advantage of having a simple analytic description of growth phenomena justifies its consideration. The analytic description in one equation of nucleus growth during primary recrystallization, secondary recrystallization, and grain boundary migration is a case in point.

The fact that a wide variety of irreversible phenomena falls within the limitations of the theory should stimulate a search for still other irreversible processes that may be so characterized and, more important, it should stimulate experimentation in the fields of interaction effects, such as thermal diffusion (diffusion due to a temperature gradient, boundary migration due to diffusion across the boundary, etc.). With respect to the latter suggestion the reader is cautioned to read DeGroot,[1] for there are limitations to the theory which should be understood. One such limitation is that no interactions in the sense of the theory would be expected to occur between a scalar flux, such as recovery, and a vector flux, such as diffusion.

A discussion of the assumptions involved in the method used to derive the rate of interface motion is in order. The unique assumptions of this method were: 1—that the production of irreversible entropy was confined mainly to the interface region, hence, by analogy with the theory as previously developed, the specific irreversible entropy production per unit area of this interface region would be quadratic in the "forces" causing motion of the interface region, and 2—that the irreversible entropy was uniformly produced over the unit area of interface considered. Whenever two fluxes of different tensor rank are involved in the interface motion, the statement that the velocity of interface motion is proportional to the free energy released per unit advance of the interface must be examined carefully. For example, in the pearlite transformation the velocity of growth is not simply proportional to the free energy released per unit advance, but is a more complex function of the dissipated energy. Finally, the theory should be applied only to those cases where the free energy released per mol traversed is less than RT.

This mode of description of boundary migration has an interesting implication; namely, that the phenomenological equations can be made mechanism-sensitive by describing the mode of nonuniform entropy production. For example, in the growth of a crystal from the vapor, there are at least two mechanisms of growth which can be considered. These mechanisms are uniform deposition on the surface at high saturation of the vapor phase and preferred deposition on the spirals emanating from screw dislocations at low saturation. In the former case the growth law is given by Eq. I-6, in the latter case a spiral migration rate must be calculated on the basis of an interface localized at the spiral: the irreversible entropy production is localized to lie in some region adjacent to the spiral. (Incidentally, the expression obtained for the rate of migration of the spiral normal to itself is proportional to the right hand side of Eq. I-6.) Then the rate of growth of the crystal must be expressed in terms of the rate of advance of the spirals. Thus, the theory will give correct results, if it is applicable to the microscopic processes that occur, and if the particular mode of nonuniform entropy production ("plane" interface of constant or varying thickness normal to the plane, "line" interface, etc.) is taken explicity into account in the equations describing the phenomenon as it appears macroscopically. Another example illustrating this point is the process of sintering. Herring[19] has considered the rate laws obtained for many different assumptions of the mechanism of sintering using the proper forces obtained from the thermodynamic theory in each case. This aspect of the mode of production of irreversible entropy must be considered in the process of applying the thermodynamic theory.

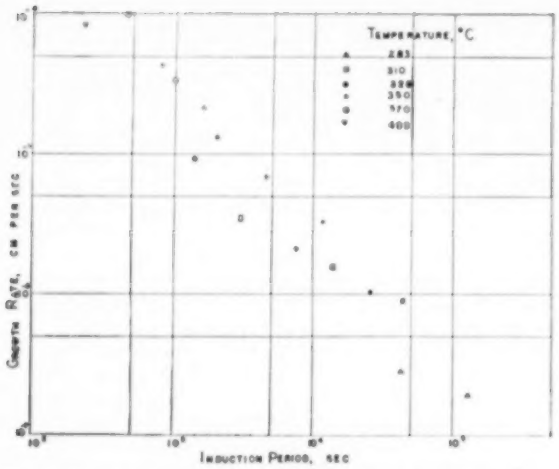

Fig. 1—Growth rate vs induction period for aluminum. Data from Anderson and Mehl.[9]

Finally, the significance of some of the results should be described here. First, it is apparent because of the correlation described in Fig. 1, that the incubation period in primary recrystallization is a consequence of slow growth and not of nucleation or transient nucleation. Second, it seems reasonable in view of the quantitative agreement obtained that the variation of the exponent in the grain growth law, $D = Kt^n$, is due to the migration of impurities along with the migration of the grain boundaries. This result is worth checking into further.

Summary and Conclusions

It is found that the thermodynamic theory of irreversible processes predicts that for many growth processes boundaries (interfaces) shall move at a rate proportional to the Gibbs free energy released per unit volume swept by the interface. However, this description is not generally true and each particular application must be considered separately in terms of the theory.

The equation applicable to growth in primary recrystallization, secondary recrystallization, or grain growth is

$$\frac{dR}{dt} = \frac{L_r}{T}\left(\Delta g_c + \Delta g_b - 2\sigma/R + \frac{\Sigma_i K_i \frac{\partial \sigma}{\partial C_i}}{R^3}\right)$$

where Δg_c is the difference in strain free energy across interface; Δg_b, the difference in free energy due to grain boundary area per unit volume on both sides of interface; σ, the interface energy per unit area; R, the radius of boundary; C_i, the concentration of i atoms in boundary; L_r, the mobility; T, the absolute temperature; K_i, a constant times number of i atoms migrating with grain boundaries; Δg_c is 0 for secondary recrystallization and grain growth; Δg_b is 0 for grain growth; and $\Sigma_i \frac{K_i}{R^3}\frac{\partial \sigma}{\partial C_i} = 0$ for pure metals.

Three results derived from this equation should be emphasized: 1—the induction period in primary as well as secondary recrystallization is due to slow growth; 2—the grain growth law $D = Kt^{1/6}$ corresponds to the case of impurities traveling with the boundaries such that $\partial\sigma/\partial C < 0$

$$\Sigma_i \frac{K_i}{R^3}\frac{\partial \sigma}{\partial C_i} >> 2\sigma/R$$

and 3—a limitation to grain growth due to impurities at the boundary is predicted for the case where $\partial\sigma/\partial C > 0$.

An interesting interaction effect is predicted between boundary migration and diffusion across the boundary, or heat and electrical flows across the boundary.

The equation applicable to the growth of spherical particles in a superheated or supercooled one component matrix is

$$\frac{dR}{dt} = \frac{L_c}{T}(\Delta g - 2\sigma/R)$$

where the terms have the same significance as for the previous case.

The equation applicable to the growth of a spherical particle of one stable phase in a supersaturated matrix is

$$\frac{dR}{dt} = K/t^{1/2}$$

where K is a function of chemical potentials and concentrations (see text), and t is time. The other terms have the same significance as before. The equations applicable to the growth of pearlite are

$$V = \frac{L_p}{T}\frac{(\Delta g - 2\sigma'/S^*_p)}{(a + S^*_p)}$$

and

$$S^*_p = 4\sigma'/\Delta g + a/2$$

where V is the velocity of growth; σ', the ferrite-cementite interface energy; S^*_p, the interlamellar spacing corresponding to maximum rate of growth; and a, the sum of ratios of mobilities (see text) which is exponentially dependent on the reciprocal of the absolute temperature. These equations are obtained by considering that not only does diffusion occur but also a chemical reaction occurs. These two processes are complementary—neither is the limiting process because the boundary conditions for one are controlled by the other.

The rate of propagation of a slip band is also treated in the text with the following result:

$$\frac{dR}{dt} = \frac{L_\tau}{T}(C\sigma - \tau/2\pi R)$$

where σ is the applied stress, and τ, the linear tension at spearhead of slipped region.

The relation between flux and force given by the theory for a uniform approach to equilibrium in the specimen is that the rate of change of some state parameter is proportional to the partial derivative of the Gibbs free energy with respect to the conjugate state parameter. In simple words, the rate of approach to equilibrium is proportional to the deviation from equilibrium. An example of this relation is found for recovery where

$$\frac{d\epsilon}{dt} = -\frac{L}{T}\epsilon$$

Here ϵ is some average internal strain. A description of slipless flow alternate to that of Herring is also given in the text. Almost all the processes

treated are specialized examples of the general theory which treats the case of more than one flux acting simultaneously.

The situation described by a continuous variation of a state parameter has not been treated in this paper because of adequate coverage elsewhere. In this case, the "force" is a gradient of a thermodynamic potential such as chemical potential, temperature, pressure, etc.

The conclusion is made that a multitude of irreversible phenomena studied in metallurgy are described by the language of the thermodynamic theory of irreversible processes. For all these processes the limitation of the theory to processes where the driving energy per atom is less than the thermal energy, kT, is obeyed.

Acknowledgment

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Technical Note

Grain Boundary Films in Boron Steels

by J. W. Spretnak and Rudolph Speiser

IT has been suggested that boron in steel may form a film entirely around the austenite grain and that this film is responsible for the boron hardenability effect. In this connection, it is of interest to examine some of the ramifications of the concentration range of boron usually employed in hardenable steels, namely 0.0005 to 0.003 pct in a grain size range of ASTM grain size No. 1 through No. 10.

The ratio of the iron to boron atoms and the number of unit cells of γ iron per boron atom are listed in Table I. Even at the highest concentration considered, there are 1600 unit cells of γ iron per boron atom, assuming a uniform distribution of boron.

To investigate the possibility of the boron film formation, the number of boron atoms required to cover the grain surface completely must be calculated. With some transition elements, boron crystallizes in sheets composed of equilateral hexagons very much like graphite.[1] The selected value for the length of a side is 1.80A. A simple calculation shows that two boron atoms cover an area of 8.4×10^{-16} sq cm. Table II lists the number of atoms of boron required for the formation of the monatomic film and Table III lists the number of boron atoms per grain. The hypothetical cases of 100 pct and 10 pct adsorption are calculated (all boron atoms in a grain and 10 pct of all boron atoms in a grain are located at the grain surface respectively). In Table III, all combinations of grain size and composition below and to the left of the solid line (100 pct adsorption) and the dashed line (10 pct adsorption) are excluded as to the possibility of covering the grain surface with a continuous boron film. Thus, even for 100 pct adsorption, the smaller grains can form the film only at the higher concentrations. For the best case, grain size No. 1 and 0.0030 pct B, the required degree of adsorption is 3.9 pct.

The above calculations deal only with the number of boron atoms required to form a monatomic film and do not take into account the mechanism of concentration of boron at the grain surface and the possible limitations to the extent of this concentration at a constant temperature, as for example in the austenitizing process. The question next arises as to how this surface concentration can occur during an isothermal treatment. Such surface enrichment of boron must occur through the phenomenon of surface adsorption, i.e., the concentration of solute atoms in solid solution in the vicinity of the surface without precipitation. A solute atom will tend to concentrate at the grain boundary if it reduces the interfacial tension. The possibility of adsorption effects involving both boron and carbon in iron has been discussed.[2] In general, the tendency for a sol-

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Table I. Ratio of Iron to Boron Atoms and Number of γ Iron Unit Cells Per Boron Atom for Various Concentrations of Boron

Wt Pct B	Ratio of Iron to Boron Atoms	No. of γ Fe Unit Cells per Boron Atom
0.0005	3.87×10^{5}	9.97×10^{5}
0.0010	1.93×10^{5}	4.83×10^{5}
0.0015	1.29×10^{5}	3.22×10^{5}
0.0020	9.68×10^{4}	2.42×10^{5}
0.0025	7.75×10^{4}	1.94×10^{5}
0.0030	6.65×10^{4}	1.66×10^{5}

Table II. Data on ASTM Grain Sizes

ASTM Grain Size No.	Mean Planar Grain Diameter,* Microns	No. of Unit Cells of γ Fe per Grain	Surface Area per Grain, Sq Cm	No. of Boron Atoms per Grain Required for Monatomic Film
1	286	2.55×10^{17}	2.57×10^{-2}	6.12×10^{12}
2	200	8.98×10^{16}	1.28×10^{-2}	3.05×10^{12}
3	143	3.20×10^{16}	6.44×10^{-3}	1.53×10^{12}
4	100	1.13×10^{16}	3.21×10^{-3}	7.64×10^{11}
5	71	3.99×10^{15}	1.61×10^{-3}	3.83×10^{11}
6	50	1.41×10^{15}	8.04×10^{-4}	1.91×10^{11}
7	35	4.99×10^{14}	4.02×10^{-4}	9.57×10^{10}
8	25	1.79×10^{14}	2.03×10^{-4}	4.83×10^{10}
9	18	6.36×10^{13}	1.02×10^{-4}	2.43×10^{10}
10	13	1.88×10^{13}	4.52×10^{-5}	1.08×10^{10}

* Mean area of grain considered as circular area.

be 0.003 pct at 970°C*; therefore the enrichment of boron in the region of the grain surface at this constant temperature is limited to this concentration. The thickness of the surface phase enriched by adsorption is not known. Assuming grain size No. 6 and that the adsorption effect is limited to a surface shell ten unit cells thick, the maximum possible adsorption for an average concentration of 0.005 pct B is 0.25 pct† for isolated grains and 0.50 pct for contiguous grains. From Table III, essentially 100 pct adsorption is required to form the film in this case. Considering only the surface layer of atoms enriched by adsorption, this amounts to 0.01 pct adsorption‡ for isolated grains and 0.02 pct for contiguous grains. Thus, from the above arguments, it is extremely unlikely that continuous or extended boron films form on austenite grain surfaces and are responsible for the hardenability effect. It is evident that the distribution of boron and Fe_2B precipitates at the grain boundary will be localized and spotty.

* Unpublished research.

† The number of unit cells in the shell is 0.61×10^{12}, which at saturation would contain 3.67×10^{6} boron atoms. A single grain contains 1.46×10^{11} boron atoms. Therefore the percent adsorption is $(3.67\times10^{6} \div 1.46\times10^{11})100$.

‡ Each cell face at the surface has two iron atoms. The number of boron atoms is at saturation $2(0.609\times10^{11}) = 0.1832\times10^{6}$; the percent adsorption is $(0.1832\times10^{6} \div 1.46\times10^{11})100 = \frac{6.65\times10^{5}}{}$ 0.01.

Table III. Number of Boron Atoms per Grain

ASTM Grain Size No.		Boron, Pct					
		0.0005	0.0010	0.0015	0.0020	0.0025	0.0030
1	10%	2.63×10^{13}	5.27×10^{13}	7.90×10^{13}	1.05×10^{14}	1.32×10^{14}	1.58×10^{14}
2		9.29×10^{12}	1.85×10^{13}	2.79×10^{13}	3.72×10^{13}	4.64×10^{13}	5.58×10^{13}
3		3.31×10^{12}	6.62×10^{12}	9.93×10^{12}	1.32×10^{13}	1.66×10^{13}	1.99×10^{13}
4		1.17×10^{12}	2.34×10^{12}	3.50×10^{12}	4.67×10^{12}	5.84×10^{12}	7.01×10^{12}
5		4.13×10^{11}	8.27×10^{11}	1.24×10^{12}	1.65×10^{12}	2.07×10^{12}	2.48×10^{12}
6	100%	1.46×10^{11}	2.92×10^{11}	4.38×10^{11}	5.84×10^{11}	7.30×10^{11}	8.76×10^{11}
7		5.17×10^{10}	1.03×10^{11}	1.55×10^{11}	2.06×10^{11}	2.58×10^{11}	3.10×10^{11}
8		1.85×10^{10}	3.69×10^{10}	5.54×10^{10}	7.39×10^{10}	9.24×10^{10}	1.11×10^{11}
9		6.58×10^{9}	1.32×10^{10}	1.97×10^{10}	2.63×10^{10}	3.29×10^{10}	3.95×10^{10}
10		1.95×10^{9}	3.89×10^{9}	5.84×10^{9}	7.79×10^{9}	9.74×10^{9}	1.17×10^{10}

ute atom to concentrate at the grain boundary would be expected to increase with an increase in temperature. Since adsorption is concentration in solid solution without precipitation, the limitation to the extent of concentration at a particular temperature is the solubility of the solute atom at this temperature. Any further concentration of boron would require the precipitation of the compound Fe_2B from solid solution. The precipitation of this compound would require that the solid solution become supersaturated with respect to boron. This supersaturation cannot occur by the adsorption mechanism at constant temperature, and such precipitation usually occurs on reducing the temperature with resulting decrease in solubility. The only possibility of precipitation at constant temperature is the case in which a second solute element such as carbon is present and also undergoes grain boundary adsorption along with boron. Thus the solubility product for boron carbide in iron could be exceeded at the grain boundary without exceeding the solubility limit of either solute atom. Such precipitation would deplete the solid solution at the grain boundary and allow further adsorption to take place.

The solubility of boron in γ iron is estimated to

Although it is quite unlikely that a grain boundary film is the underlying boron hardenability mechanism, the possibility of adsorption effects involving boron in solid solution in austenite appears to be of primary importance in explaining some aspects of the boron hardenability effect. For example, the metallographic test for boron[5] and the optimum austenitizing range[3, 4] for boron steels can be rationalized in terms of adsorption effects.

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Measurement of Particle Sizes in Opaque Bodies

by R. L. Fullman

IN the investigation of metallurgical transformations and the relationships between microstructure and properties of metals, it frequently is desirable to obtain a measurement of the relative amounts of the various phases present and of the mean size of particles into which each phase is dispersed. The relative amounts of the phases can be measured by the classical methods of area, lineal, and point analysis,[1-3] in accordance with the principle that the volume fraction of a phase, the fraction of a polished cross section occupied by the phase, the fraction of a random line occupied by the phase, and the fraction of randomly arrayed points occupied by the phase are all equal. The validity of this relationship depends only on the attainment of a truly random sample of area, length, or points, and not on the size, shape, or distribution of the particles constituting the phase. Smith and Guttman[4] have derived a relationship between the interface area per unit volume S_v and the measurable quantities L_a, the interface length per unit area on a cross section, and N_L, the number of interfaces per unit length intersected by a random line. Their equation,

$$S_v = \frac{4}{\pi} L_a = 2N_L$$

is also valid regardless of the distribution of particle sizes and shapes.

In contrast to the situation concerning measurement of relative fractions of phases and of interface area, the measurement of particle sizes in opaque samples has not been subjected to a complete analysis. It has been common to measure some lineal or area dimension of particles on a polished cross section and to use the mean value as a qualitative measure of particle size. In the present paper, quantitative relationships are established among the various mean dimensions on a polished cross section and the actual dimensions of the particles present.

Particles of Uniform Size

Spheres: If a metal sample contains particles of a phase α dispersed in the form of spheres of uniform size, a polished cross section through the sample will reveal circular areas of phase α with radii from 0 to r, the radius of the spheres. Consider a cube of unit dimensions to be cut from the sample. If a cross section parallel to one of the cube faces is examined, the average number of particles per unit area (N_s) equals the number of particles per unit volume (N_v) times the probability p_i that the plane would intersect a single sphere positioned at random within the unit cube. Since, of the various possible positions for the cross-sectional plane over the unit length from top to bottom of the cube, only those positions existing over the length $2r$ would lead to the plane intersecting the sphere, the probability of intersecting a single sphere is just $2r$.

$$N_s = N_v\, p_i = N_v \cdot 2r \qquad [1]$$

Applying the equality of area and volume fractions, the relationship is found between sphere size and average area $\bar{s}$ of uniform spheres intersected by a random cross section,

$$f = N_v V = N_v \cdot \frac{4}{3}\pi r^3 = N_s \bar{s} = N_v \cdot 2r\bar{s}$$

$$\bar{s} = \frac{2}{3}\pi r^2 \qquad [2]$$

A similar analysis reveals the average traverse length across spheres of uniform size when random lines are passed through the sample. If a randomly oriented unit cube is cut from the sample and a randomly positioned line is passed through the cube parallel to a cube edge, the number of spheres intersected by the line (N_L) equals the number of spheres per unit volume times the probability p_i of the line hitting a single randomly placed sphere in the cube. Since possible positions of the line occupy unit area, and possible positions for which it will pass through the sphere occupy an area of πr^2, the probability of the line hitting a randomly placed single sphere is πr^2.

$$N_L = N_v\, p_i = N_v\, \pi r^2 \qquad [3]$$

Combining this relationship with the equality of volume and lineal fraction, the desired relationship is obtained between radius and mean lineal traverse length $\bar{l}$, for spheres of uniform size.

$$f = N_v V = N_v \cdot \frac{4}{3}\pi r^3 = N_L \bar{l} = N_v \cdot \pi r^2 \bar{l}$$

$$\bar{l} = \frac{4}{3} r \qquad [4]$$

Circular Plates: Consider a sample containing particles of a phase α in the form of circular plates of uniform radius r and thickness t, where $r >> t$. If the plates are randomly oriented, as in a sufficiently large sample of a fine grained polycrystalline material, area and lineal analysis may be carried out with parallel cross-sectional planes and lineal traverses. If the plates are not randomly oriented, it is necessary to randomize the orientation of the cross-sectional planes and traverse directions. Let a unit cube be cut from the sample, and a cross-section plane be passed through the cube parallel to one of the cube faces. The number of plates cut by the cross-sectional plane per unit area is equal to the number of plates per unit volume times the probability of a plate intersecting a single randomly positioned and randomly oriented plate in the cube. If J is the component of the plate diameter in the direction normal to the cross-sectional planes, the probability of a plane cutting a single randomly oriented plate is equal to $\bar{J}$, the mean value of J for all possible orientations of the plate.

Let ϕ be the dihedral angle between a plate and the cross-sectional plane, and let $p_\phi\, d\phi$ be the probability that a plate makes an angle between ϕ and $\phi + d\phi$ with the cross-sectional plane. Then for ran-

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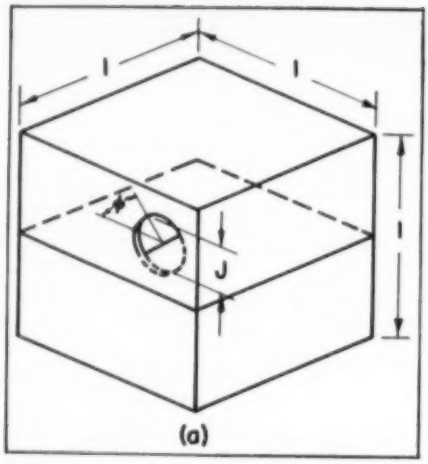

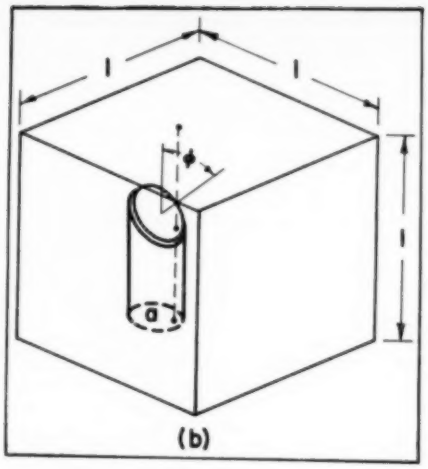

Fig. 1—Intersections of a circular plate in a unit cube with (a) a cross-sectioning plane and with (b) a lineal traverse.

domly oriented plates, $p_\phi = \sin \phi$. Let $p_J dJ$ be the probability that a given plate has a diameter component perpendicular to the cross-sectional plane between J and $J + dJ$. Referring to Fig. 1a,

$$J = 2r \sin \phi$$

$$p_J = p_\phi \left| \frac{d\phi}{dJ} \right| = \frac{\tan \phi}{2r}$$

The average value of J for all orientations is equal to the integral, over all possible values of J, of the product of J and its probability.

$$\overline{J} = \int_0^{2r} J\, p_J\, dJ = \frac{\pi}{2} r$$

$$N_s = \overline{J}\, N_v = \frac{\pi}{2} r\, N_v \qquad [5]$$

Combining Eq. 5 and the equality of volume and area fraction, the desired relationship is obtained between plate size and average area of particles intersected by a random cross section.

$$f = N_v V = N_v\, \pi r^2 t = N_s \overline{s} = \frac{\pi r}{2} N_v \overline{s}$$

$$\overline{s} = 2rt \qquad [6]$$

If random lines parallel to an edge of the unit cube are passed through a sample, the number of plates per unit length intersected by the lines is equal to the number of plates per unit volume times the probability that a line will intersect a single randomly positioned and randomly oriented plate in the cube. If a is the apparent area of a plate as viewed from the direction of the lines, the probability of a line cutting a single randomly positioned and oriented plate is equal to the mean value of a, averaged over all possible plate orientations. If ϕ is the angle between the lineal traverses and the normal to a plate, this angle is completely equivalent to that defined above, with respect to its probability of existence. Referring to Fig. 1b,

$$a = \pi r^2 \cos \phi$$

$$p_a = p_\phi \left| \frac{d\phi}{da} \right| = \frac{1}{\pi r^2}$$

Again integrating to find the mean value of the apparent area, $\overline{a}$, the result is

$$\overline{a} = \int_0^{\pi r^2} a\, p_a\, da = \frac{1}{\pi r^2} \int_0^{\pi r^2} a\, da = \frac{\pi r^2}{2}$$

$$N_L = \overline{a}\, N_v = \frac{\pi r^2}{2} N_v \qquad [7]$$

Combining Eq. 7 with the equality of volume and lineal fractions, the desired value is obtained of the mean traverse length $\overline{l}$ for plates of uniform size.

$$f = N_v V = N_v\, \pi r^2 t = N_L \overline{l} = N_v \frac{\pi r^2}{2} \overline{l}$$

$$\overline{l} = 2t \qquad [8]$$

Rods: Consider a sample containing a phase α in the form of randomly oriented rods of radius r and length H, where $H >> r$. A unit cube cut from the sample is cut by a plane parallel to a cube face. Let J be the component of rod length in the direction normal to the cross-section planes. Then the number of rods per unit area on the cross section is equal to the number of rods per unit volume times the probability that a single randomly positioned and oriented rod is cut by a plane. Hence, the number per unit area is equal to the number per unit volume times the mean value of J, averaged over all rod orientations. Let ϕ be the angle between a rod and the direction perpendicular to the cross-section planes. Referring to Fig. 2a,

$$J = H \cos \phi$$

p_ϕ is again equal to $\sin \phi$, so that

$$p_J = p_\phi \left| \frac{d\phi}{dJ} \right| = \frac{1}{H}$$

$$\overline{J} = \int_0^H J\, p_J\, dJ = \int_0^H \frac{J}{H}\, dJ = \frac{H}{2}$$

$$N_s = N_v \overline{J} = \frac{N_v H}{2} \qquad [9]$$

Combining Eq. 9 with the equality of volume and area fractions, the desired value is found of the mean area of rods intersected by a random cross section.

$$f = N_v V = N_v\, \pi r^2 H = N_s \overline{s} = \frac{N_v H}{2} \overline{s}$$

$$\overline{s} = 2\pi r^2 \qquad [10]$$

If straight lines are passed through the unit cube parallel to one of the cube edges, the number of rods per unit length intersected along the line is equal to the number per unit volume times the probability p_l that a single line hits a single randomly positioned and oriented rod. The latter probability is equal to the average area $\bar{a}$ presented by randomly oriented rods viewed from the direction of the lines. Let ϕ be the angle between the axis of a rod and the direction of the lines. Then, referring to Fig. 2b,

$$a = 2rH \sin \phi$$

p_a is again equal to $\sin \phi$, so that

$$p_a = p_\phi \left| \frac{d\phi}{da} \right| = \frac{\tan \phi}{2rH}$$

$$\bar{a} = \int_0^{2rH} a\, p_a\, da = 2rH \int_0^{\pi/2} \sin^2 \phi\, d\phi = \frac{\pi r H}{2}$$

$$N_L = \bar{a} N_v = \frac{\pi r H}{2} N_v \qquad [11]$$

Combining Eq. 11 and the equality of lineal and volume fractions, the desired value of the mean lineal traverse across randomly oriented rods of uniform size is found.

$$f = N_v V = N_v \pi r^2 H = N_L \bar{l} = \frac{\pi r H}{2} N_v \bar{l}$$

$$\bar{l} = 2r \qquad [12]$$

Note that neither the average cross-sectional area nor the average lineal traverse of particles in the form of long thin rods depends on the length of the rods. It does not appear possible to measure the length of particles in this shape by any of the usual measurements on polished cross sections. This fact demonstrates immediately the impossibility of finding a relationship between measured quantities and any sort of "average particle dimension" that would apply regardless of particle shape.

Combinations of Point, Lineal, and Area Analysis for Particles of Uniform Size: While the measurement of average lineal traverse or average particle area sectioned is sufficient to describe the particle size, as shown in the preceding sections, some other simple relationships may be established which are useful in that they sometimes permit the use of simpler experimental methods. For example, combining Eqs. 1 and 3, the result is

$$r = \frac{2}{\pi} \frac{N_L}{N_a} \qquad [13]$$

This relationship permits measuring the radius of uniform spheres by merely counting the number of spheres intersected per unit length of traverse and the number of spheres intersected per unit area of cross section. The necessity for actually measuring either lineal traverse lengths or areas intersected on the cross section is eliminated. For the special instance of grain size measurement, where the volume fraction equals 1, either count alone is sufficient. Then

$$r = \frac{3}{4N_L} = \sqrt{\frac{3}{2\pi N_a}} \qquad [14]$$

Eqs. 1 and 3 may also be combined to yield the number of particles per unit volume

$$N_v = \frac{\pi}{4} \frac{N_a^2}{N_L} \qquad [15]$$

or to provide a means of measuring the volume fraction of a phase dispersed as uniform spheres.

$$f = \frac{8}{3\pi} \frac{N_L^2}{N_a} \qquad [16]$$

For circular plates, Eqs. 5 and 7 may be combined to permit measurement of several quantities of interest.

$$r = \frac{N_L}{N_a} \qquad [17]$$

$$t = \frac{f}{2N_L} \qquad [18]$$

$$N_v = \frac{2}{\pi} \frac{N_a^2}{N_L} \qquad [19]$$

For rods a similar combination of Eqs. 9 and 11 leads to the following relationships:

$$r = \frac{1}{\pi} \frac{N_L}{N_a} \qquad [20]$$

$$f = \frac{2}{\pi} \frac{N_L^2}{N_a} \qquad [21]$$

Another quantity of frequent interest in quantitative metallography is the mean free path between

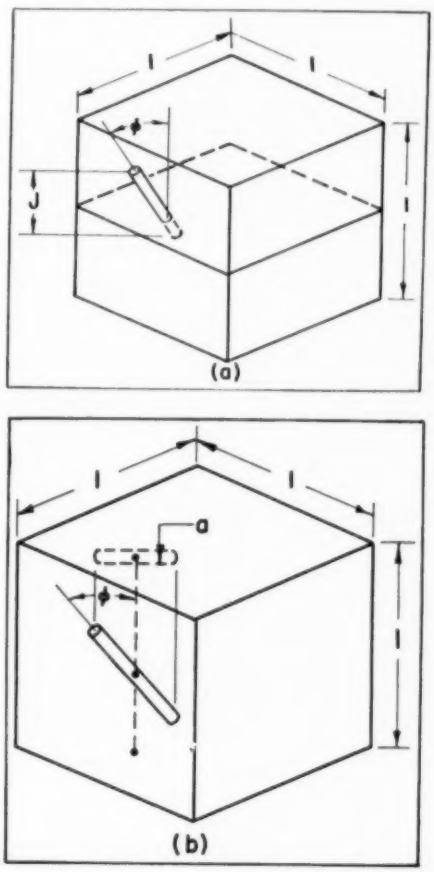

Fig. 2—Intersections of a rod in a unit cube with (a) a cross-sectioning plane and with (b) a lineal traverse.

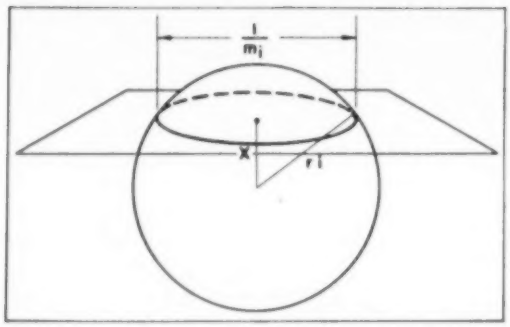

Fig. 3—Intersection of a sphere with a cross-sectioning plane.

particles. The mean free path P may always be found from the relationship

$$P = \frac{1 - f}{N_L} \qquad [22]$$

which is valid regardless of the shape or distribution of sizes of the particles. Other measures of the mean free path may be obtained by combinations of the relations already found for particles of uniform size and shape, but these do not appear to offer any significant advantage over the general formula.

Particle Size in Samples with Nonuniform Size Particles

The simple relationships developed in the previous section apply precisely only if the particle size is uniform, but they may be used for approximate measurements provided that the range of particle sizes is small. If more accurate measurements are desired, or if there is a large range of particle sizes, the variation in particle size must be taken into account. The necessary analysis for determining the complete distribution of particle sizes present when the particles are in the form of spheres has been carried out by Hagermann,[7] Scheil and coworkers,[8-10] and Huber.[11] The equations presented above for plates and rods may be combined with the general methods of approach used by these authors to develop methods for measurement of the complete distribution of particle size for these shapes as well. However, the measurement of mean particle sizes for samples containing a distribution of sizes can be measured more easily than the complete distribution function, and these mean values frequently provide an adequate description of the structure. For example, a complete description of the kinetics of a transformation occurring by nucleation and growth is obtained if the number of particles per unit volume, as well as the volume fraction occupied by a new phase, is determined as a function of the transformation time and temperature.

Spheres: Consider a sample containing particles of a phase α in the form of spheres of various radii. If the particles are divided into groups according to their radius, then for each group with radius arbitrarily close to some value r_i, equations analogous to Eqs. 1 to 4 may be written

$$N_{s_i} = 2r_i N_{v_i} \qquad [1a]$$

$$\bar{s}_i = \frac{2}{3}\pi r_i^2 \qquad [2a]$$

$$N_{L_i} = \pi r_i^2 N_{v_i} \qquad [3a]$$

$$\bar{l}_i = \frac{4}{3} r_i \qquad [4a]$$

Combining these relationships and summing over all values of the radius r_i, the following expressions for $\bar{s}$ and $\bar{l}$ are obtained:

$$\bar{s} = \frac{\Sigma_i N_{s_i} \bar{s}_i}{\Sigma_i N_{s_i}} = \frac{\Sigma_i N_{v_i} V_i}{2\Sigma_i N_{v_i} r_i} = \frac{\bar{V}}{2\bar{r}} \qquad [23]$$

$$\bar{l} = \frac{\Sigma_i N_{L_i} \bar{l}_i}{\Sigma_i N_{L_i}} = \frac{\Sigma_i N_{v_i} V_i}{\pi \Sigma_i N_{v_i} r_i^2} = \frac{4\bar{V}}{\bar{A}} \qquad [24]$$

where $\bar{A}$ is the average surface area of the spheres.

In order to separate the mean values of r, A, and V from Eqs. 23 and 24, it is necessary to add a new measurement. Let m_i be the reciprocal of the diameter of the circle of intersection of a sphere of radius r_i with a cross-section plane. Then, referring to Fig. 3,

$$m_i = \frac{1}{2\sqrt{r_i^2 - x^2}}$$

where x is the distance of the cross-section plane from the center of the sphere. If $p_x\,dx$ is the probability that a cross-section plane cuts a sphere of radius r_i at a distance x to $x + dx$ from its center, then

$$p_x = \frac{1}{r_i}$$

If $p_{m_i}\,d_{m_i}$ is the probability of finding a reciprocal diameter between m_i and $m_i + dm_i$,

$$p_{m_i} = p_x \left| \frac{dx}{dm_i} \right| = \frac{1}{2\,m_i^2\,r_i\sqrt{4\,m_i^2\,r_i^2 - 1}}$$

The mean value of m_i is equal to the integral, over all possible values of m_i, of its value times the probability of its existence at that value.

$$\bar{m}_i = \int_{\frac{1}{2r_i}}^{\infty} m_i\, p_{m_i}\, dm_i = \frac{\pi}{4\,r_i}$$

Summing these mean values of $\bar{m}_i$ over all sphere sizes and dividing by the total number of observations, an expression is obtained for the mean value $\bar{m}$ for the whole sample.

$$\bar{m} = \frac{\Sigma_i N_{s_i} \bar{m}_i}{\Sigma_i N_{s_i}} = \frac{\pi \Sigma_i N_{v_i}}{4\Sigma_i N_{v_i} r_i} = \frac{\pi}{4\bar{r}} \qquad [25]$$

Combining Eq. 25 with Eqs. 23 and 24, the necessary relationships between various mean dimension descriptions of the spheres and the several measurable quantities $\bar{l}$, $\bar{s}$, $\bar{m}$, and f are obtained.

$$\bar{r} = \frac{\pi}{4\bar{m}} \qquad [26]$$

$$\bar{V} = \frac{\pi\,\bar{s}}{2\,\bar{m}} = \frac{\pi f}{2\,\bar{m}\,N_v} \qquad [27]$$

$$\bar{A} = \frac{2\,\pi\,\bar{s}}{\bar{m}\,\bar{l}} = \frac{2\,\pi\,N_L}{\bar{m}\,N_v} \qquad [28]$$

$$N_v = \frac{2\,\bar{m}\,f}{\pi\,\bar{s}} = \frac{2\,\bar{m}\,N_L}{\pi} \qquad [29]$$

Circular Plates: When the particles under consideration are in the form of circular plates with a

distribution of radius r and thickness t, this distribution may be divided into a number of arbitrarily small ranges of particles of radius r_i and within each such range of radii the plates may be further subdivided into arbitrarily small ranges of thickness t_j. Then for each range of particle size, equations equivalent to Eqs. 5 to 8 may be written.

$$N_{s_{ij}} = \frac{N_{v_{ij}} V_{ij}}{\bar{s}_{ij}} = \frac{\pi}{2} N_{v_{ij}} r_i \qquad [5a]$$

$$s_{ij} = 2 r_i t_j \qquad [6a]$$

$$N_{L_{ij}} = \frac{N_{v_{ij}} V_{ij}}{\bar{l}_{ij}} = \frac{\pi}{2} N_{v_{ij}} r_i^2 \qquad [7a]$$

$$\bar{l}_{ij} = 2 t_j \qquad [8a]$$

Adding the contributions of all particle size ranges to the total number per unit area and per unit length observed, the following is obtained:

$$\bar{s} = \frac{\Sigma_i \Sigma_j N_{L_{ij}} \bar{l}_{ij}}{\Sigma_i \Sigma_j N_{v_{ij}}} = \frac{2 \Sigma_i \Sigma_j N_{v_{ij}} V_{ij}}{\pi \Sigma_i \Sigma_j N_{v_{ij}} r_i} = \frac{2 \bar{V}}{\pi \bar{r}} \qquad [30]$$

$$\bar{l} = \frac{\Sigma_i \Sigma_j N_{L_{ij}} \bar{l}_{ij}}{\Sigma_i \Sigma_j N_{L_{ij}}} = \frac{2 \Sigma_i \Sigma_j N_{v_{ij}} V_{ij}}{\pi \Sigma_i \Sigma_j N_{v_{ij}} r_i^2} = \frac{4 \bar{V}}{\bar{A}} \qquad [31]$$

In order to separate the various mean dimensions from these equations, and in order to find a measure of the mean plate thickness, it is necessary to introduce three more measurable quantities.

Let E be the reciprocal of the length of intersection of a plate with a cross-sectioning plane. Then referring to Fig. 4,

$$E_i = \frac{1}{2\sqrt{r_i^2 - x^2}}$$

where x is the distance from the center of the plate to its intersection with the cross-sectioning plane. If $p_x dx$ is the probability that the plate is intersected by the cross-sectioning plane at a distance between x and $x + dx$ then

$$p_x = \frac{1}{r_i}$$

Let $p_{E_i}\, dE_i$ be the probability that the reciprocal of the intersection length lies between E_i and $E_i + dE_i$. Then

$$p_{E_i} = p_x \left| \frac{dx}{dE_i} \right| = \frac{(r_i^2 - x^2)^{3/2}}{r_i x}$$

The mean value of E_i is equal to the integral of the product of E_i and the probability of its existence, over all possible values of E_i.

$$\bar{E}_i = \int_{\frac{1}{2r_i}}^{\infty} E_i\, p_{E_i}\, dE_i = \frac{\pi}{4 r_i}$$

Summing the values of $\bar{E}_i$ over all values of the plate radius r_i the following is obtained:

$$\bar{E} = \frac{\Sigma_i N_{v_i} \bar{E}_i}{\Sigma_i N_{v_i}} = \frac{\pi \Sigma_i N_{v_i}}{4 \Sigma_i N_{v_i} r_i} = \frac{\pi}{4 \bar{r}} \qquad [32]$$

In order to find a measure of the average plate thickness, a quantity F is defined as the reciprocal of the width of an intersection of a plate with a cross-sectioning plane. Then, referring to Fig. 4, if

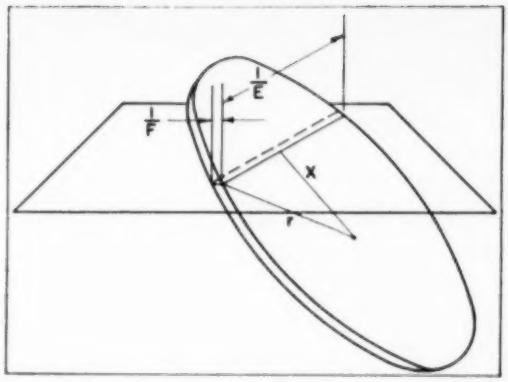

Fig. 4—Intersection of a circular plate with a cross-sectioning plane.

ϕ is the dihedral angle between the plate and the cross-sectioning plane,

$$F_{ij} = \frac{\sin \phi}{t_j}$$

In the present instance the probability function of ϕ required is the probability of *cutting* a plate at angle ϕ with the cross-sectioning plane, so that it is the probability that a plate lies at an angle ϕ with the sectioning plane times the probability that a plate lying at this angle will be cut by the plane. Since both of these probabilities are proportional to $\sin \phi$,

$$p_\phi = K \sin^2 \phi$$

If $p_{F_{ij}}\, dF_{ij}$ is the probability that the reciprocal of cross-section width lies between F_{ij} and $F_{ij} + dF_{ij}$, its value is

$$p_{F_{ij}} = p_\phi \left| \frac{d\phi}{dF_{ij}} \right| = K t_j \frac{\sin^2 \phi}{\cos \phi}$$

where the constant K may be evaluated from the fact that the sum of the probabilities of all possible values of F_{ij} must equal 1.

$$\int_0^{1/t_j} p_{F_{ij}}\, dF_{ij} = K \int_0^{\pi/2} \sin^2 \phi\, d\phi = \frac{\pi}{4} K = 1$$

Therefore,

$$p_{F_{ij}} = \frac{4}{\pi} t_j \frac{\sin^2 \phi}{\cos \phi}$$

The mean value of F_{ij} is equal to the integral, over all possible values of F_{ij}, of the product of F_{ij} and its probability.

$$\bar{F}_{ij} = \int_0^{1/t_j} F_{ij}\, p_{F_{ij}}\, dF_{ij} = \frac{4}{\pi t_j} \int_0^{\pi/2} \sin^2 \phi\, d\phi = \frac{8}{3 \pi t_j}$$

Summing the values of F_{ij} over all values of the plate radius and thickness and dividing by the number of observations of all plate sizes,

$$\bar{F} = \frac{\Sigma_i \Sigma_j N_{v_{ij}} \bar{F}_{ij}}{\Sigma_i \Sigma_j N_{v_{ij}}} = \frac{3 \Sigma_i \Sigma_j N_{v_{ij}} \frac{r_i}{t_j}}{3 \pi \Sigma_i \Sigma_j N_{v_{ij}} r_i} = \frac{8}{3 \pi} \frac{\left(\frac{\bar{r}}{t}\right)}{\bar{r}} \qquad [33]$$

If the ratio of radius to thickness of the plates is

independent of the plate radius, Eq. 33 provides a measure of the mean plate thickness, since, under these conditions,

$$\overline{F} = \frac{8}{3\pi\overline{t}} \qquad [33a]$$

However, if the radius-to-thickness ratio is not independent of plate size, the mean plate thickness may still be found by measurement of the ratio of width to length of intersections of plates with the cross-sectioning plane. Let G be this ratio; then

$$G_{ij} = \frac{t_j}{2\sin\phi\sqrt{r_i^2 - x^2}}$$

where ϕ and x have the same meanings as previously. As before the probability functions for ϕ and x may be written as follows:

$$p_\phi = \frac{4}{\pi}\sin^2\phi$$

$$p_x = \frac{1}{r_i}$$

In this case the probability function for G depends on both the probability functions of ϕ and x.

$$p_{G_{ij}} = \int_0^{\sqrt{r_i^2 - t_j^2/4G_{ij}^2}} p_\phi \left|\frac{\partial\phi}{\partial G_{ij}}\right| p_x\,dx = \frac{t_j^2}{2r_i^2 G_{ij}^3}$$

The mean value of G is equal to the integral, over all possible values of G, of the product of G and its probability.

$$\overline{G}_{ij} = \int_{t_j/2r_i}^{\infty} G_{ij}\,p_{G_{ij}}\,d\,G_{ij} = \frac{t_j}{r_i}$$

Summing over all plate sizes,

$$\overline{G} = \frac{\Sigma_i\Sigma_j N_{v_{ij}}\overline{G}_{ij}}{\Sigma_i\Sigma_j N_{v_{ij}}} = \frac{\Sigma_i\Sigma_j N_{v_{ij}} t_j}{\Sigma_i\Sigma_j N_{v_{ij}} r_i} = \frac{\overline{t}}{\overline{r}} \qquad [34]$$

Combining Eqs. 30 to 34, the desired relationships between the mean values of plate dimensions and the mean values of the several measurable quantities are obtained.

$$\overline{r} = \frac{\pi}{4\overline{E}} \qquad [35]$$

$$\overline{t} = \frac{\pi\overline{G}}{4\overline{E}} \qquad [36]$$

$$\overline{V} = \frac{\pi^2\overline{s}}{8\overline{E}} = \frac{\pi^2 f}{8\overline{E}N_v} \qquad [37]$$

$$\overline{A} = \frac{\pi^2\overline{s}}{2\overline{E}\,\overline{l}} = \frac{\pi^2 N_L}{2\overline{E}N_v} \qquad [38]$$

$$N_v = \frac{8\overline{E}f}{\pi^2\overline{s}} = \frac{8\overline{E}N_v}{\pi^2} \qquad [39]$$

$$\left(\frac{\overline{r}}{t}\right) = \frac{3\pi^2\overline{F}}{32\overline{E}} \qquad [40]$$

If the ratio of plate radius to thickness is independent of plate size,

$$\left(\frac{\overline{r}}{t}\right) = \frac{\overline{r}}{\overline{t}}$$

so

$$\frac{1}{\overline{G}} = \frac{3\pi^2\overline{F}}{32\overline{E}} \qquad [41]$$

This relationship provides a means of checking on whether or not the radius-to-thickness ratio depends on plate size.

Rods: Since the analysis of rods, even of uniform size, does not permit separation of the rod length from the number of rods per unit volume, it does not appear profitable to pursue the analysis of rods of nonuniform size. Fortunately, most metallurgical transformations lead to the formation of particles in the form of either spheres or plates so that our inability to analyze the particle size of rod-shaped particles is not a serious limitation.

Summary

Methods have been developed for the analysis of particle size measurements by area and lineal analysis when the particles are in the form of spheres, plates, or rods. Methods that are valid when there is a wide range of particle sizes were developed, as well as simpler methods which apply when the particle size is uniform. It was shown that the usual types of observation do not permit measurement of the length of rod-shaped particles. For such particles there is a negligible probability that a cross-sectioning plane will cut along the rod length, so that statistical observations of the dimensions of intersections of the particles with a cross-sectioning plane depend only on the rod's radius. Despite this limitation, the method permits description of the distribution of phases present in commonly encountered metallurgical samples.

Acknowledgment

The author had frequent discussions with J. C. Fisher, who also read the manuscript.

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aime NEWS

Refractories, Latin American Coking Coals, Agglomeration And Beneficiation Are Topics at Blast Furnace And Open Hearth Conferences

THE 36th Conference of the Blast Furnace, Coke Oven, and Raw Materials Committee and National Open Hearth Steel Committee will be held at the Statler Hotel, Buffalo, N. Y., Apr. 20 to 22, 1953. All operating men, repair and maintenance men, metallurgists, ceramic and refractory engineers, observers, and any others interested in the production of more steel, better steel and cheaper steel and in any of the problems connected with the reduction of iron ore in the blast furnace, are invited to attend.

The registration fee for either Conference is $7, which includes a copy of the respective Proceedings when printed. There is no registration fee for students at any of the sessions, unless they desire a copy of the Proceedings. AIME Members are entitled to a $2 reduction in the registration fee upon presentation of their membership card.

Adequate hotel facilities will be provided at the Statler and other Buffalo hotels. Hotels, however, will not hold blocks of rooms assigned to this meeting after April 5. Single rooms are limited. Hotel reservation requests should be sent directly to the hotel of your choice as soon as possible. Be sure to mention the Blast Furnace or Open Hearth Conference of AIME, as well as the time of arrival.

Through the courtesy of the Bethlehem Steel Co. and the Symington-Gould Co., simultaneous inspection trips have been planned for Wednesday, April 22. The Bethlehem trip will afford an opportunity to see all of the operations at the Lackawanna plant, and the Symington-Gould trip will show the operation of a cold metal plant. Busses for both trips will leave the Genesee St. entrance to the Hotel Statler at 8:30 am. Luncheon arrangements have been taken care of by the host companies.

A charge of $2.50 will be made by the two Committees to help defray the plant trip transportation costs.

Preliminary Program of Blast Furnace, Coke Oven, and Raw Materials Conference

SUNDAY, APRIL 19

4 to 9 pm
Registration

MONDAY, APRIL 20

8 am to 5 pm
Registration

9:30 am
Agglomeration and Beneficiation Session:
Beneficiation of Texas ores; quality control of blast furnace flue dust sinter; reduction-oxidation process of magnetic roasting for taconites; construction and application of sintering fans.

2:00 pm
Blast Furnace General Session:
Studies of the tuyere zone; low shaft blast furnace; use of Brazilian ore; blast furnace operation.

TUESDAY, APRIL 21

9 am to 5 pm
Registration

9:30 am
Coal and Coke Session:
Production and improvement of coke from Latin American coking coals; past and future of carbonization research; gas pressure measurements within the coal charge in coke ovens.

9:30 am
Blast Furnace Blowing in Practice Session:
At Inland; at Lorain Works of National Tube Co.; at American Steel & Wire Co.

12:30 pm
Luncheon Meeting:
Everyone attending the Blast Furnace, Coke Oven, and Raw Materials sessions is invited to attend this luncheon and business meeting.

2:00 pm
Blast Furnace Operation Session:
Operating at high top pressure; distribution of materials in the furnace; optimum composition of blast furnace slag; instrumentation.

6:30 pm
Reception

7:00 pm
Annual Fellowship Dinner

WEDNESDAY, APRIL 22

8 am to 4 pm
Registration

8:30 am
Plant trip

Preliminary Program Of National Open Hearth Conference

SUNDAY, APRIL 19

4 to 9 pm
Registration

MONDAY, APRIL 20

8 am to 5 pm
Registration

9:30 am
General Session:
Announcements and reports; McKune Award paper.

10:30 am
Training Open Hearth Personnel Session:
Supervision, furnace crews, casting crews, maintenance crews in new shops and old shops.

10:30 am
Acid Operating Session:
Open hearth sand specifications; sand for acid open hearth furnaces; question and answer discussions.

2:00 pm
Operating Metallurgy Session:
Quality problems, open hearth vs electric furnace; production and quality of screw steels; rimmed vs capped steel; surface quality of aluminum killed sheet steels; thermocouple bath temperature measurements; coating molds.

2:00 pm
Refractories and Masonry Session:
Effect of restricted uptake on refractory consumption and production rate; flue dust and slag removal; monolithic refractories in furnace spouts; checker problems, economics of port and construction.

TUESDAY, APRIL 21

9 am to 5 pm
Registration

9:30 am
Fuels and Combustion Session:
Continuous oxygen analysis for combustion control; atomization of liquid fuels; significance of air preheat; firing methods; heating up furnaces after rebuilds.

2:00 pm
Hot Metal Basic Operations Session:
Trends in furnace design; new bottoms and bottom repair; effect of melt carbon on production rates; productivity by use of oxygen lance and sulphur limitations; mechanical aids in the open hearth.

2:00 pm
Cold Effect and Basic Foundry Practice Session:
Economics of the electric furnace vs open hearth with cold charge; effects of reduced aluminum additions on quality of castings; effects of ladle sizes, refractories, etc. on quality; use of rammed and castable refractories in runners, bottoms, etc.; effects of residual alloys on hot tears.

6:30 pm
Reception

7:00 pm
Annual Fellowship Dinner

WEDNESDAY, APRIL 22

8 am to 4 pm
Registration

8:30 am
Plant trip

New England Regional Conference Program Set

THE Seventh Annual New England Regional Conference of the Institute of Metals Div., AIME, is scheduled to be held at the General Electric Research Laboratory, The Knolls, Schenectady, N. Y., Apr. 23 to 25, 1953.

The program will open on Thursday afternoon with sessions on *Deformation* and *Research in the Schenectady Area*. An *Extrusion* session followed by a tour of the GE Laboratory are planned for Friday. The Banquet is scheduled for 7 pm Friday at the Hotel Van Curler, tickets will cost $5. The speaker for the evening will be Dr. Katherine Blodgett. The last conference session, *New Techniques in Metallurgy*, will take place Saturday morning.

Registration will be at the General Electric Research Laboratory Thursday, April 23, from 1 to 2 pm. Fee for the Banquet and registration will be $6. Fee for registration alone will be $2. AIME Student Associates may register free of charge, while nonmember students will be charged $1.

Chairman of the Conference Committee is J. H. Moore, National Research Corp. Serving with him on the Committee are W. H. Sharp, Pratt & Whitney Aircraft, Vice-Chairman; F. H. Wilson, American Brass Co., Secretary; L. P. Tarasov, Norton Co., Treasurer; A. I. Blank, Chase Brass & Copper Co., Past Chairman; Dan Cushing, consultant metallurgist; W. D. Robertson, Yale University; W. L. Stearns, Bridgeport Brass Co.; L. W. Thelin, Chase Brass & Copper Co.; M. B. Bever, MIT, and G. P. Swift, consulting engineer. J. E. Burke, Knolls Atomic Power Laboratory, and T. W. Landig, Research Laboratory, were GE representatives.

All noncitizens except Canadians attending the Conference must request approval of visit to the laboratory by March 20. Please write: J. P. Garey, IGE, Room 600, Building 36, Schenectady Works, Schenectady, N. Y. Letters should include name, nationality, foreign residence and city, affiliation in the U. S., residence and city.

There are a limited number of single and double rooms available and all planning to attend the meeting are requested to write directly to the Hotel Van Curler, Schenectady, N. Y. for room reservations, mentioning the AIME New England Regional Conference.

THURSDAY, APRIL 23

1 to 2 pm
Registration

2 to 5 pm
Deformation

Current Theories of Deformation: J. C. Fisher, General Electric Co.

Deformation and Surface Defects: T. A. Read, Columbia University.

Spontaneous Deformation During Transformation: A. H. Geisler, General Electric Co.

Deformation at High Temperatures: N. J. Grant, Massachusetts Institute of Technology

7 to 9 pm

Research in the Schenectady Area

Metallurgical Research at General Electric Co.: J. H. Holloman

Metallurgical Research at Knolls Atomic Power Laboratory: J. E. Burke

Metallurgical Research at Rensselaer Polytechnic Institute: Arthur A. Burr

Metallurgical Research at Turbine Div. Laboratory, General Electric Co.

FRIDAY, APRIL 24

9 am to 12 m

Extrusion

Extrusion Principles: D. K. Crampton, Chase Brass & Copper Co.

Extrusion of Aluminum: E. S. Bunn, Revere Copper & Brass, Inc.

Glass Lubricated Extrusion: J. Strauss, Vanadium Corp. of America

2 to 5 pm

Guided Tour of General Electric Laboratory

6 pm

Social Hour

7 pm

Banquet

Interference Colors Reflected by Thin Films: Katherine Blodgett, General Electric Co.

SATURDAY, APRIL 25

9 am to 12 m

New Techniques in Metallurgy

Techniques in the Measurement of Temperature: J. M. Berry, General Electric Co.

Techniques for Investigation of Radiation Effects in Metal: C. E. Weber, Knolls Atomic Power Laboratory

Electrochemical Techniques in Physical Metallurgy: W. D. Robertson, Yale University

ECPD Lists Accredited Metallurgical Engineering Colleges

As a service to its readers, JOURNAL OF METALS is publishing the mineral industry portion of the 1952 list of "Accredited Undergraduate Engineering Curricula in the United States." This list, revised annually, is issued by the Education Committee of the Engineers Council for Professional Development, and covers all phases of engineering education. The AIME is actively represented on ECPD, which was jointly organized by the Founder Societies and various other groups interested in the professional recognition of engineers.

ECPD is merely authorized by its constituent organizations to publish a list of accredited engineering curricula for use as desired by those agencies which require such a list. It has no authority to impose any restrictions or standardizations upon engineering colleges, nor does it desire to do so. On the contrary it aims to preserve the independence of action of individual institutions and to promote thereby the general advancement of engineering education.

METALLURGICAL ENGINEERING

Alabama, University of (1949)
Arizona, University of (1950)
California, University of (Berkeley)
Carnegie Institute of Technology
Case Institute of Technology
Cincinnati, University of (1948)
Colorado School of Mines
Columbia University
Cornell University (1951)
Fenn College (1948)
Harvard University (Physical Metallurgy)
Idaho, University of (Metallurgy) (1938)
Illinois Institute of Technology (1949)
Illinois, University of
Kentucky, University of
Lafayette College
Lehigh University
Massachusetts Institute of Technology (Metallurgy)
Michigan College of Mining and Technology
Michigan, University of
Minnesota, University of
Missouri School of Mines and Metallurgy
Montana School of Mines
Notre Dame, University of (Metallurgy) (1942)
Ohio State University
Pennsylvania State College (Metallurgy) (1938)
Pennsylvania, University of (1949)
Pittsburgh, University of
Purdue University (1941)
Rensselaer Polytechnic Institute (1938)
South Dakota School of Mines
Stanford University (1952)
Utah, University of
Virginia Polytechnic Institute (1948)
Washington, State College of
Washington, University of
Wayne University (1950)
Wisconsin, University of
Yale University (Metallurgy)

MINING ENGINEERING

Alabama, University of
Alaska, University of (includes Geological 5-yr. option) (1941)
Arizona, University of
California, University of (Berkeley)
Colorado School of Mines
Columbia University
Idaho, University of (1938)
Illinois, University of
Kentucky, University of
Lafayette College
Lehigh University
Michigan College of Mining and Technology
Minnesota, University of
Missouri School of Mines and Metallurgy (Mine; includes Petroleum option (1941); Mining Geology option (1950)
Montana School of Mines
Nevada, University of
North Dakota, University of
Ohio State University (Mine)
Pennsylvania State College (1938)
Pittsburgh, University of
South Dakota School of Mines
Stanford University (1952)
Texas Western College (formerly Texas College of Mines and Metallurgy) (1947) (includes option in Mining Geology and Metallurgy)
Utah, University of
Virginia Polytechnic Institute (1948)
Washington, State College of
Washington, University of
West Virginia University
Wisconsin, University of

1953 Blast Furnace Officers Nominated

The following have been nominated as officers in 1953 for the AIME, Blast Furnace, Coke Oven and Raw Materials Committee:

Chairman: C. C. Russell, Koppers Co., Inc. (Presently Vice-Chairman).

Vice-Chairman: W. E. Marshall, Armco Steel Corp. (Presently Chairman of the Program Committee).

Secretary: E. J. Andberg, Globe Iron Co. (Presently Chairman of the Membership Committee).

Executive Board: R. P. Liggett for a 4-year term.

AIME Names 1955 IMD Lecturer

Dr. Clarence Zener, associate director of the Westinghouse Research Laboratory, East Pittsburgh, Pa., has been selected to deliver the Institute of Metals Div. Lecture for 1955.

Doherty Fund Increased

Supplementing a gift of Surface Combustion Corp. debentures with a face value of $46,000, three further gifts, in cash, have been made for the establishment of the Henry L. Doherty Memorial Fund. The Cities Service Co. has contributed $25,000; the W. Alton Jones Foundation, Inc., $15,000; and the Frueauff Foundation, $10,000. It is understood that the principal of the Fund is to remain inviolate, only the income being used for designated purposes related to the petroleum industry.

Announce Student Prize Paper Winners

Announcement was made at the Annual Meeting of the winners of the National Student Prize Paper Contest. Each author receives $100.

Graduate Division: Bruce W. Gilbert, *Shore Scleroscope Hardness Tests Made on Mohs' Scale Minerals from Talc to Quartz, Inclusive*, entered by Chicago Section. William Fred Hofmeister, *Stress Corrosion Cracking of Plain Carbon and Low-Alloy Steels in Sulphuric Acid*, also entered by the Chicago Section.

Undergraduate Division: Benjamin C. Allen, *A Study of Carbide Solution in Austenite of a 6-4-4-2 High-Speed Steel*, entered by the Philadelphia Section. Marvin A. Kunde, *The Agglomeration of Taconite Concentrate*, entered by the Colorado Section. David F. Drinkhouse, *An Abandoned Iron Deposit, Durham, Pa.*, entered by Lehigh Valley Section.

The AIME will again sponsor a competition during the current academic year.

The competition is open only to Student Associates of the Institute. Two divisions have been set up for the contest, graduate and undergraduate.

The AIME will cooperate with Sections and Student Chapters wishing to hold preliminary local competitions to determine representatives in the national contest. In the national contest, three cash prizes of $100 each will be awarded to the three top papers, while two $100 awards will be given in the graduate division. Students in Local Sections not holding competitions are eligible to enter the national competition directly. However, papers must be submitted to local Section Secretaries for screening.

All papers submitted must represent as completely as possible original work of the author in interpreting experimental results and in writing the paper. Illustrations must be suitable for reproduction.

A special board of judges will choose winners of the national competition. The board chairman will present awards at the next Annual Meeting.

E. Hayes Addresses Columbia Subsection

Earl T. Hayes, chief of the physical metallurgy branch, U. S. Bureau of Mines, Region II, Albany, Ore., addressed the Columbia Subsection on *Zirconium Metallurgy Today* at the group's first meeting of the new year.

Speaking at the Spokane Hotel, Spokane, Wash., he told the group that the Bureau of Mines plant at Albany, Ore. is the only place where zirconium is being extracted in the nation, at a rate of more than 100,000 lb yearly.

He described the process which involves exclusion of air in the manufacturing and melting of zirconium. Basically it involves reduction of zirconium chloride with molten magnesium, under an atmosphere of helium, Mr. Hayes said.

Mr. Hayes also stated that about 20,000 to 25,000 tons of zircon sands are being used annually by U. S. industry for ceramics, refractories, and chemicals.

Connecticut Section Holds Student's Night

The Connecticut Section observed its annual student's night at the third technical meeting of the season at Hammond Laboratory, Yale University, New Haven, Conn.

R. P. Kytle, Jr., director, sheet and foil products, Reynolds Metals Co., Louisville, Ky., addressed the group on *Applications of Aluminum*. The Reynolds film, *Pigs and Progress*, preceded his lecture. Mr. Kytle traced the history of the aluminum industry in the U. S. Among the possible uses for aluminum alloys, Mr. Kytle mentioned clad aluminum condenser tubes for condenser and heat exchangers and aluminum radiators for the automotive industry.

Students attending the meeting were introduced by William E. Milligan, faculty advisor to the Yale Student Chapter of AIME. David H. Thompson, American Brass Co., Chairman of the Connecticut Section, made introductory remarks. Leon Thelin, Chase Brass & Copper Co., Vice-Chairman of the Connecticut Section, served as technical chairman for the meeting and introduced the speaker.

Divisional Interest Should Be Specified

Every member of AIME is entitled to indicate *one* division as his primary interest and to belong to one or more of the 10 professional divisions serving the membership. By notifying AIME headquarters which division or divisions you wish to be affiliated with you are automatically placed on the mailing list of these divisions and thus will receive special division communications, notices, and news letters, if any. Such affiliation is now shown in the geographical section of the Directory. More than one third of the membership have made no selections. The 10 professional divisions of AIME are as follows: Mining, Geology and Geophysics Div., Coal Div., Industrial Minerals Div., Minerals Beneficiation Div., Extractive Metallurgy Div. (nonferrous), Iron and Steel Div. (production), Institute of Metals Div. (ferrous and nonferrous physical metallurgy), Petroleum Div., Mineral Industry Education Div., and the Mineral Economics Div.

Write to the Secretary, AIME, 29 West 39th St., New York 18, N. Y., advising of the divisions with which you wish to be affiliated indicating *one* division as your primary interest.

Establish Southern California Subsection

Basil Kantzer, Chairman of the Southern California Section, requested the Board's permission for establishment of the Southern Sierra Subsection of the Southern California Section, which was granted. The San Francisco Section had indicated its willingness to release all of Mono and Inyo Counties and that part of Kern County east of the Sierras north of Mojave, and part of San Bernardino County north and northeasterly of Highway 466.

Apr. 15, 1953 is the deadline for all Institute of Metals Div. papers that are to be presented at the AIME Fall Meeting.

Speaker Named For Northwest Conference

George Vincent, public relations officer for the Aluminum Co. of Canada, Ltd., will address the metals luncheon, Saturday, May 16 at the second Pacific Northwest Metals & Minerals Conference, May 14 to 16. The Kitimat-Kemano project now under development in British Columbia will be the subject of his address. One of the largest Canadian undertakings ever to be financed by free enterprise, the Alcan project includes a major hydroelectric development, an aluminum smelter, and construction of a new community having a projected ultimate population of 50,000.

All events during the Conference will take place at the Benjamin Franklin Hotel, Seattle.

Income Shows Surplus

AIME income for 1952 totaled $593,381, compared with $522,076 in 1951, and expenses amounted to $575,315, compared with $514,067 in the previous year. The surplus was therefore $18,065. Of this amount, $10,000 will be returned to the Special Fund for Publications, which was almost wiped out during the years of deficits, and the rest credited to surplus account. All of the expense for the Directory, which was not issued in 1951, was charged in the 1952 accounts though not actually mailed until 1953. This totaled $20,542, including the entire labor expense of the Flexoprint installation which permitted the Directory itself to be printed for about half of the cost heretofore incurred. It is planned to publish the Directory annually hereafter, beginning about June 1954; a supplement will be issued in June 1953, with the names of the committee personnel and Local Section, Division, and Branch officers for the current year.

On a Branch accounting basis, the Mining Branch had a surplus of $27,075; the Petroleum Branch a surplus of $6850, and the Metals Branch a deficit of $15,860, largely because of the relatively large volume of physical metallurgy papers.

AIME Contributes To ECPD Engineering Study

AIME is contributing $400 to Engineers Council for Professional Development for a special study of the adequacy and standards of engineering education. Other constituent sessions of ECPD are also contributing their share, and the Engineering Foundation is supplying $3000.

Student Associate Transfers Facilitated

To facilitate transfer of Student Associates to the grade of Junior Membership in the Institute, all present requirements as to formal application were removed by action of the Directors at the December meeting of the Executive and Finance Committees. During the past year, to effect the transfer it has been necessary for the Student Associate to make out a formal application and have it endorsed by a member. Even though this was not a formidable handicap to the change of status, many Student Associates did not take the trouble to make application and were therefore dropped from the rolls at the end of the year of graduation.

It was voted "that effective in 1953, Student Associates shall automatically become Junior Members at the end of the year in which they finish school; that they shall be so advised at an appropriate time and be billed for Junior Member dues for the following year. No formal application or endorsements shall be required. If acceptance of election is not received by March 31, the Junior Member thus elected will be dropped."

Student Associates who were required to change status by Dec. 31, 1952 are not under the new ruling.

The meeting of the AIME Bessemer Steel Committee was held at the Duquesne Club in Pittsburgh on January 14 with 30 in attendance. Bessemer superintendents of all producing plants, with one exception, were in attendance. Dr. R. C. Buehl of the U. S. Bureau of Mines and Mr. F. B. Skeates of Link-Belt Co. were guest speakers on side blown converter operation.
First Row: W. P. Holloway, Wheeling Steel Corp.; R. E. Edwards, Jones & Laughlin Steel Corp.; R. C. Buehl, U. S. Bureau of Mines; A. B. Wilder, National Tube div., U. S. Steel Corp.; F. B. Skeates, Link-Belt Co.; G. McMorran, C. M. Kay, U. S. Steel Corp.; L. A. Xidis, Wheeling Steel Corp. Second Row: A. C. Philp, Wheeling Steel Corp.; K. Gordon, Weirton Steel Co.; J. M. Stone, Tennessee Coal & Iron div., U. S. Steel Corp.; W. H. Mayo, U. S. Steel Corp.; H. C. Dunkle, Republic Steel Corp.; L. R. Eisenhart, Bethlehem Steel Co.; W. G. McDonough, National Tube div., U. S. Steel Corp., J. W. Kirkpatrick, M. G. Morrison, Youngstown Sheet & Tube Co.; J. D. Sutherland, U. S. Steel Corp.; G. M. Yocom, Wheeling Steel Corp. Third Row: J. J. Veselich, Weirton Steel Co.; E. P. Best, A. M. Byers Co.; W. M. Zatezalo, Weirton Steel Co.; J. P. Ely, National Tube div., U. S. Steel Corp.; D. J. Taylor, Jones & Laughlin Steel Corp.; R. J. Walter, Wheeling Steel Corp.; W. R. McLain, U. S. Steel Corp.; R. C. Johnston, R. E. Woodbury, Republic Steel Corp.; L. T. Sanchez, J. W. Schroeder, National Tube div., U. S. Steel Corp.

Personals

John E. Anderson is with the General Electric as a metallurgical engineer in the works laboratory, Trenton, N. J.

C. W. Jordan, Jr. has accepted the position of metallurgist with the Shakeproof div., Illinois Tool Co., Elgin, Ill.

Russel Heath has joined the div. of industrial research, Washington State College, Pullman, as an assistant metallurgist.

Frank Marold is associated with the Warren Foundry & Pipe Corp., New York, N. Y.

Alexander Ross has been appointed chief engineer and **H. R. Sennstrom,** executive engineer, locomotive div., American Locomotive Co., Schenectady, N. Y.

F. J. TOKAR

F. J. Tokar is service engineer with the Quigley Co., Chicago.

R. Lindley Murray, president of Hooker Electrochemical Co. has been awarded honorary membership in the American Institute of Chemists.

Wade B. Houk has been appointed general superintendent, South works, American Steel & Wire Div., U. S. Steel Corp. Mr. Houk had been division superintendent of the South works' wire mills.

Grant A. Sattem has been promoted from general sales manager to vice-president in charge of sales, Luria Engineering Co.

Harold W. Lownie, Jr., has been appointed to a supervisory post at Battelle Memorial Institute's process metallurgy laboratories. Prior to joining Battelle in 1946, he had been associated with Westinghouse Electric Corp.

P. B. TURSI

Peter Budd Tursi has been named chief metallurgist, the Riverside Metal Co., Riverside, N. J. Mr. Tursi has been associated with the firm since 1936.

Kenneth C. Vincent has been appointed supervisor of extraction metallurgy at Armour Research Foundation of Illinois Institute of Technology, Chicago. Before joining the Foundation, Dr. Vincent was chief metallurgist for the Baroid sales div., National Lead Co., Houston.

L. A. Watts has been named general manager of sales for the eastern div. of the Colorado Fuel & Iron Corp.

William A. Reich has been appointed manager of the advance development engineering at the Carboloy dept., General Electric Co., Detroit.

G. O. Loach, director and vice-president, Electro Metallurgical Co. of Canada, Ltd., has been appointed assistant manager of its Welland plant.

G. O. LOACH

A. Kingsley Ferguson has been appointed vice-president in charge of industrial engineering for Walter Kidde Constructors, Inc.

Edmund C. Harder, senior geologist for Aluminum Ltd. and subsidiaries, has been appointed a member of the board of directors.

S. L. Jackson has been named district manager of the Los Angeles office, Electro Metallurgical Co. **R. L. Reed** has been appointed district manager of the Detroit office.

H. M. Williams has been appointed equipment engineer and **E. W. Ruhe,** mechanical projects engineer for the metals div., Olin Industries, Inc.

James S. Walker has been named manager of technical service for the Hooker Electrochemical Co.

D. A. RHOADES

D. A. Rhoades, Kaiser Aluminum & Chemical Corp., Oakland, Calif., was elected president of the Aluminum Assn. for the coming year. **A. V. Davis,** Aluminum Co. of America, New York was reelected chairman of the board and **Donald M. White** was reappointed secretary and treasurer.

Peter Patriarca, formerly of Rome Air Development Co., has been appointed to the staff of the Oak Ridge National Laboratory.

L. K. Sillcox, formerly executive vice-president, New York Air Brake Co., Watertown, N. Y., has been appointed vice-chairman of the board, New York, N. Y.

H. E. McDonnell has retired as superintendent of blast furnaces and coke plant, Weirton Steel Co., Weirton, W. Va.

John E. Griffith has been named assistant chief industrial engineer,

Jones & Laughlin Steel Corp., Pittsburgh.

John B. Merrill was appointed vice-president in charge of metallurgical and chemical operations for the Sylvania Electric Products Inc.

U. B. Corsini has been named general superintendent of the Steel & Wire works of the American Steel & Wire div., U. S. Steel Corp., Donora, Pa.

S. D. Kirkpatrick has been elected chairman of the Atomic Energy Commission's Advisory Committee on Industrial Information.

E. D. Powers was elected president of Chemical Construction Corp. He well remain as vice-president and director of American Cyanamid Co. **W. N. Porter** was elected chairman of the board of directors. Major General Porter had been president.

R. J. Leary has been appointed extractive metallurgist in the pyrometallurgy branch of the U. S. Bureau of Mines at Pittsburgh. He formerly was development metallurgist at the Duquesne works of the U. S. Steel Corp.

Andrew B. Black is associated with the metallurgical research div. of Sherritt-Gordon Mines, Ottawa as an engineer. He had been located in Peru.

Robert R. Blackwood is metallurgical engineer in the A. C. spark plug div., General Motors Corp.

A. Tregoning Cape is with the Superweld Corp., North Hollywood, Calif.

Robert W. Pelz has been appointed assistant to the director of research, Ferro Corp., Cleveland.

C. W. Jordan, Jr., is metallurgist with the Shakeproof div. of Illinois Tool, Elgin, Ill.

Ross Saylor has been named sales associate for the Columbia Steel & Shafting Co., Pittsburgh.

James L. Wyatt has joined the scientific staff of Horizons, Inc., Cleveland. Dr. Wyatt will be assistant to the technical manager.

W. B. Boyer has been elected treasurer of the Republic Steel Corp. and **Harold L. Farling** was named chief metallurgist of the Cleveland district steel plant.

Robert M. Nichols has been elected president and treasurer of Great Lakes Pressed Steel Corp., Buffalo. **J. J. Wallace** was named vice-presi-president and secretary, and **G. Adolphson** elected chairman of the board.

Reynold C. MacDonald was named superintendent of blooming and structural mills, Kaiser Steel Corp., Oakland, Calif.

William P. Hill has been promoted to assistant to vice-president, Steel div., Bethlehem Steel Co., Sparrows Point. **John S. Marsh** was named assistant chief of research and **John K. Killmer** becomes chief metallurgist.

Don W. Blend was promoted to division director of operations, Detroit divisional headquarters, Calumet & Hecla Copper Co.

Arthur F. Erwin has been appointed manager, atomic power section, Allis-Chalmers Mfg. Co. and **Edward F. Brill** appointed chief engineer.

R. L. Hanes has been appointed assistant to the vice-president in charge of sales, Colorado Fuel & Iron Corp. Mr. Hanes has been associated with CF&I since 1929.

Victor Brown has been elected a vice-president of the Kropp Forge Co., Chicago. Mr. Brown, who was formerly assistant to the president, joined the company in 1942 as chief metallurgist.

William E. Mahin, director of research at Armour Research Foundation of Illinois Institute of Technology, has been reappointed a member of the National Advisory Committee for Aeronautics.

Francis T. Letchfield was elected to the board of directors, Oliver United Filters, Inc., replacing **John B. Keating,** retired.

Russel J. Keller has joined Cleveland Welding Co., subsidiary of American Machine & Foundry Co., as engineering assistant to the president.

Obituaries

Harold E. Hostetter (Member 1944) died on Nov. 11, 1952. Mr. Hostetter was a native of South Bend, Ind. After graduation from Purdue University (M.S.E., 1935) he joined Armco Steel Corp. at Middletown, Ohio as a research assistant. Two years later he became associated with Climax Molybdenum Co., Detroit, as metallurgical engineer. In 1938 he was transferred to St. Louis. At the time of his death he was located in Detroit for Climax.

John Leighton Bray (Member 1923) died on Dec. 6, 1952. Dr. Bray had been on the staff of Purdue University since 1923 and was also head of the school of chemical and metallurgical engineering from 1935 to 1947. He was born in Millbridge, Mass. in 1890. Dr. Bray graduated from Massachusetts Institute of Technology in 1912 and obtained a doctorate in 1930. He had several years experience in Central and South America, taught at MIT and Nova

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Scotia Technical College. Before joining Purdue he was with the U. S. Tariff Commission in Washington. He was the author of various textbooks in the field of metallurgy.

Samuel S. Marshall, Jr. (Member 1946), retired, died on Dec. 8, 1952. Mr. Marshall was a native of Pittsburgh, Pa. In 1903 he joined the Jones & Laughlin Steel Corp. in the engineering dept. He held the position of assistant general superintendent of the Eliza dept. from 1917 to 1926. He was transferred to the South Side dept. for two years and was then made general superintendent of South Side works. In 1929 he became general superintendent of the Pittsburgh works. For one year Mr. Marshall was assistant general manager of the corporation and in 1937 was appointed vice-president in charge of manufacturing operations.

Charles H. Bliem (Member 1935) has died. He had been manager of the Weatherly Steel Co., Weatherly, Pa.

A. D. Riley (Member 1923), consulting engineer, Pittsburgh, died on Oct. 25, 1952. Born at Braddock, Pa., he graduated from the University of Pittsburgh in 1898. Following his graduation Mr. Riley joined the National Tube Co. as a draftsman. He became associated with the Dominion Iron & Steel Co., Sydney, Cape Breton Island in 1900 and then returned to National Tube. For two years he was associated with the Ball & Wood Co. as superintendent of the pipe dept. In 1907 Mr. Riley joined the Vacuum Engineering Co. and remained with this firm for approximately five years. He then joined the Standard Chemical Co., Canonsburg, Pa. as a mechanical engineer. In 1933 Mr. Riley opened his offices as consulting engineer in Pittsburgh.

Thure William Anderson (Member 1951), has died, according to Institute records. Mr. Anderson had been affiliated with the U. S. Steel Co., formerly Carnegie Illinois Steel Co., from 1899 to 1944. He was born in Chicago and began his career as an office boy. He held the positions of draftsman, open hearth helper, electric furnace melter, and turn foreman, respectively. Mr. Anderson later joined Eothermic Alloys Sales & Service, Inc., as sales engineer.

NECROLOGY

Date Elected	Name	Date of Death
1921	A. W. Ambrose	Dec. 28, 1952
1925	Charles H. Herty, Jr.	Jan. 17, 1953
1938	George W. Levangie	Jan. 7, 1953
1915	W. L. Maxson	Jan. 8, 1953
1943	Halbert M. McClain	Unknown
1936	Maxwell N. Short	Unknown
1929	Peter Trotzig	Unknown

Proposed for Membership

— Metals Branch AIME —

Total AIME membership on Dec. 31, 1952 was 18,643; in addition 1964 Student Associates were enrolled.

ADMISSIONS COMMITTEE

T. D. Jones, Chairman; Thomas G. Moore, Vice-Chairman; Harold S. Bell, F. W. Hanson, R. H. Chadwick, T. W. Nelson, J. H. Scaff, John T. Sherman, A. C. Brinker, Ivan Given, C. A. R. Lambly, G. P. Lutjen, E. A. Prentis, and C. Leslie Rice, Jr.

The Institute desires to extend its privileges to every person to whom it can be of service, but does not desire as members persons who are unqualified. Institute members are urged to review this list as soon as possible and immediately to inform the Secretary's office if names of people are found who are known to be unqualified for AIME membership.

In the following list C/S means change of status; R, reinstatement; M, Member; J, Junior Member; A, Associate Member; S, Student Associate.

Alabama
Birmingham—Walker, Jack D. (M) (C/S—J-M)

California
Fontana—Lytle, Edward M. (A) (C/S—S-A)
Lawndale—Conaty, Francis H. (M)
Livermore—Mash, Donald R. (J) (C/S—S-J)
Menlo Park—Porro, Emo D. (M) (C/S—A-M)

Colorado
Gilman—Witthauer, Foster J. (J) (C/S—S-J)

Florida
Lakeland—Breathitt, Harvie W., Jr. (M)

Idaho
Kellogg—Breckenridge, Robert N. (M)
Pocatello—Davis, Gedale D. (J) (C/S—S-J)
Stibnite—Wilde, Willard D. (M) (R.C/S—S-M)

Illinois
Berwyn—Luetzow, Howard J. (J)
Chicago—Boquist, Carl W. (J)
Chicago—McAndrew, Joseph B. (M) (C/S—A-M)
Chicago—Miller, Julian F. (M)
Lombard—Walker, Joseph L. (J)

Indiana
Gary—Hunter, Charles J. (M)
Hammond—Eidam, Robert E. (J) (C/S—S-J)
Hammond—Kirkland, Charles F. (M)

Kentucky
Lexington—Fox, James E. (J) (C/S—S-J)
Lexington—McHargue, Carl J. (J) (C/S—S-J)

Massachusetts
Boston—Fitzpatrick, John McNeil (M) (C/S—A-M)
Cambridge—Averbach, Benjamin L. (M) (C/S—J-M)

Michigan
Ann Arbor—Atwell, Albert A. (J)
Dearborn—Daugherty, T. S. (J) (C/S—S-J)
Detroit—Coopes, Richard J. (M)
Midland—Clark, John B. (J) (C/S—S-J)
Northville—Alexander, Lewis W. (C/S—A-M)

Minnesota
Minneapolis—Bitsianes, Gust (M) (C/S—A-M)

Montana
Great Falls—Westgard, Sherman R. (M)

Nebraska
Omaha—Curnow, Leonard T. (M)

New Jersey
Butler—Brown, Clayton Dodge (A)
Metuchen—Fisher, Harold R. (M) (C/S—A-M)
Metuchen—Luedeman, Robert T. (M) (C/S—J-M)
Rutherford—Shuris, Robert S. (J) (C/S—S-J)
Westfield—Hadley, Chester (C/S—S-A)

New Mexico
Santa Rita—Coppe, George F., Jr. (M) (C/S—A-M)

New York
Albany—Imperato, Louis G. (M)
Larchmont—Springmeyer, Allan H. (J)
Long Island City—Hodi, Frank (J) (C/S—S-J)
New York—Metzger, Marvin (M) (C/S—S-M)
Niagara Falls—Schulte, Charles A. J. (M) (C/S—J-M)
Tonawanda—Conant, Louis A. (M)
Wantagh—Roll, Kempton H. (M) (C/S—J-M)

Ohio
Beachwood—Gorman, Daniel J. (A)
Canton—Johnson, Robert J. (M) (C/S—A-M)
Cleveland—Grala, Edward M. (J) (C/S—S-J)
Cleveland Hts.—Volmar, Allan R. (J) (C/S—S-J)
Columbus—Bauer, Arthur A. (J) (C/S—S-J)
Columbus—Wheeler, David L. (J) (C/S—S-J)
Euclid—Beaver, Wallace W. (M) (C/S—A-M)
Monroe—Woods, Arthur P., Jr. (M)
Poland—Sutherland, John D. (M)
Portsmouth—Lewry, Richard William (M)
Warrensville Height—Stricker, Charles D. (J)

Oregon
Portland—Gow, James T., Sr. (M)

Pennsylvania
Ambridge—Teleshak, Stephen (J)
Beaver—Harter, Isaac, Jr. (M)
Bethlehem—Bennett, Donald C. (J)
Cornwall—Wheeler, Robert M. (M) (R.C/S—S-M)
Easton—Spang, Clarence M. (M)
Homestead Park—Richards, Earl L. (J) (C/S—S-J)
Latrobe—Roberts, George A. (M) (C/S—J-M)
Malvern—Cook, John W. (M)
Palmerton—Gamble, David L. (M)
Philadelphia—Stellabotte, Michael L. (J) (C/S—S-J)
Pittsburgh—Binstock, Martin H. (J)
Pittsburgh—Bunshah, Rointan F. (J) (C/S—S-J)
Pittsburgh—Clark, Robert L. (M)
Pittsburgh—Harrison, David K. (A)
Pittsburgh—Lipsitt, Harry A. (J)
Pittsburgh—Maxton, Robert C. (J) (C/S—S-J)
Pittsburgh—Rice, Orville D. (M)
Washington—Kaufman, Sidney F. (J) (C/S—S-J)

Tennessee
Knoxville—Hobbs, Joseph T., Jr. (M) (C/S—A-M)

Texas
Corpus Christi—Gilmore, Robert C. (A)
Dallas—Perry, Robert D. (J) (C/S—S-J)
Houston—Sosoka, John R. (J)
Houston—Steijn, Roelof P. (M) (C/S—S-M)

Utah
American Fork—Mayer, Robert C. (M)
Garfield—Baldee, Lorenzo (M)
Garfield—Comstock, Philip (M) (C/S—A-M)
Garfield—Koropp, Karl H. (M) (R.C/S—J-M)
Magna—Whitton, Hurlock G. (M)
Salt Lake City—Fish, Carlton R. (M) (R.C/S—Auto. A-M)
Salt Lake City—Forbes, Gordon B., Sr. (M)
Salt Lake City—Pardoe, James F. (J)

Virginia
Richmond—Bylund, Linton D. (M) (C/S—A-M)

Washington
Longview—Cole, Richard E. (M) (C/S—S-M)
Richland—Smith, William R. (J) (C/S—S-J)
Spokane—Williams-Dean, Nesbit (J) (C/S—S-J)

Brazil
Est. S. Paulo—Silva, Antonio A. (M)

Canada
Ontario, Welland—Texter, Alex C. (M) (R. M)
Shawinigan Falls—McLaren, Robert S. (M)

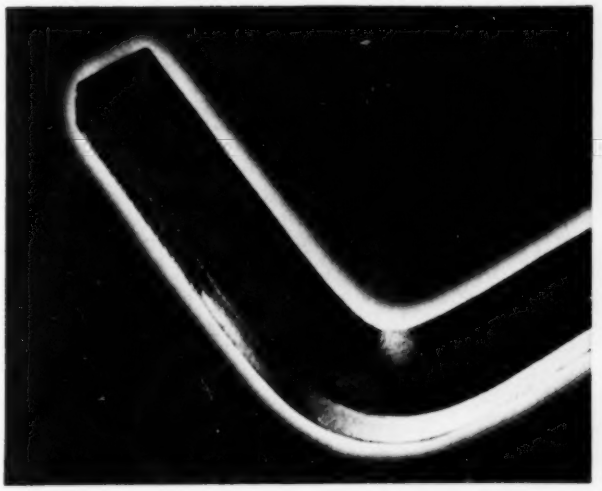
Germany
Taunus—Adams, Robert R. (M)

Japan
Tokyo—Watanabe, Seiichiro (M)

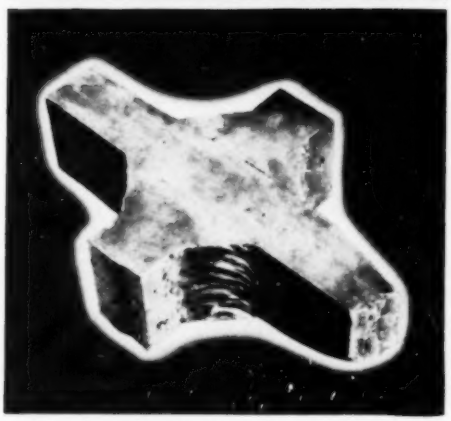
Mexico
Mexico D.F.—Becker, William (M)
Monterrey—Dill, David B., Jr. (M) (C/S—J-M)

New Zealand
Auckland—Alexander, Douglas (A) (R.C/S—S-A)

90° BEND AT 98 BELOW! This sample, flame-cut from 1" CARILLOY T-1 plate, was chilled to -98 F., and then bent to a full 90° angle. Even though the raw, flame-cut edge made up the outer radius of the bend, there was no sign of failure!



New steel has yield strength of over 90,000 psi yet remains ductile at 70°F. below zero even after welding or flame-cutting



100% WELD STRENGTH—Tensile tests on T-Steel specimens like these were made to determine the strength of the welds. These welds develop the full strength of the parent metal. Note that breaks occur outside the heat-affected zone, showing that the heat of welding has not harmed the strength of the material. No special pre-heating or post-heating treatments are required beyond those used with ordinary structural steels.

THIS remarkable steel, U·S·S CARILLOY T-1, offers great promise to those who need a super-strong steel that can be welded, flame-cut or cold-formed.

CARILLOY T-1 is unique. It differs from all other very strong steels in important respects: Its yield strength of over 90,000 psi is *not* lowered by welding or flame-cutting. In these operations, no pre-heating or stress-relieving is required. As a result, CARILLOY T-1 can be readily field welded.

Usually, welded steels of such high strength level suffer a loss of ductility at low temperatures unless elaborate precautions are taken in the welding operation. In striking contrast, notched bend weldability tests show that T-1 steel will remain ductile and tough down to the lowest atmospheric temperatures. As a matter of fact, T-1 steel, after flame-cutting, has been bent to a full 90° angle at temperatures as low as −100°F., without any sign of cracking.

Service tests show that CARILLOY T-1 is well suited for extremely abusive service, and the fact that it can be field welded should greatly lower the difficulties and cost of major repairs. In applications in which tension is the principal stress, thicknesses can often be reduced to one-third of those required with ordinary structural steels.

CARILLOY T-1 steel is another result of United States Steel's active research program which has enabled manufacturers to improve their production methods and make better products, too. A folder outlining the properties of this new steel is available. Write United States Steel Corporation, Room 2811-A, 525 William Penn Place, Pittsburgh 30, Pa

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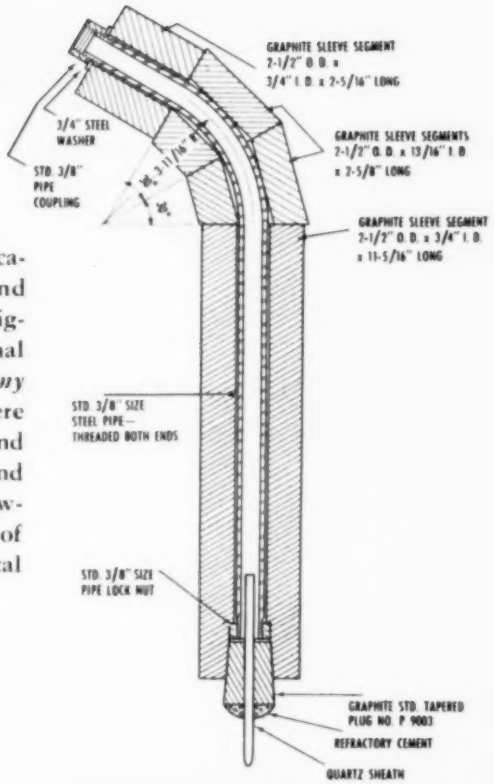
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2-1/2" O.D. x
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3/4" STEEL WASHER
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x 2-5/8" LONG
STD. 3/8" PIPE COUPLING
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2-1/2" O.D. x 3/4" I.D.
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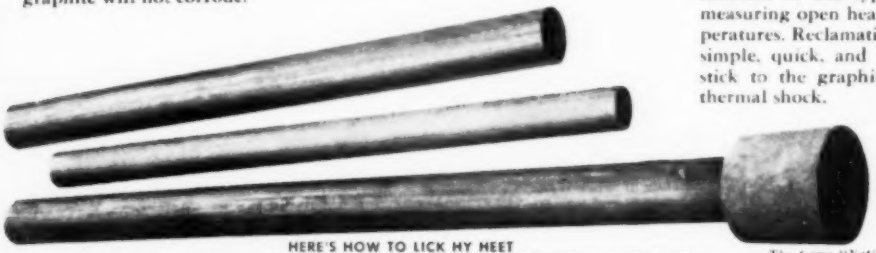
Can't be equalled by any other mate[illegible]duction of purifying gases into molten metal. Graphi[illegible] melt in the bath, can't contaminate the metal. Its low coefficient of expansion prevents cracking and spalling. Metal and dross do not adhere tightly to it. And whatever gases are used, graphite will not corrode.



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